Kuskokwim River Middle Mile Fiber Technical Feasibility Study
RD-RU-COOP-25-09

Reliability Analysis

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Rural Utility Service

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Table of Contents

List of Tables

List of Figures

Introduction

At the most basic level, the feasibility of constructing and operating a fiber-optic cable route in the Kuskokwim River depends on the demonstration that reliable long-term operation is possible. Demonstration that reliable operation is possible in this feasibility study is achieved through modeling and simulation of the system under a set of risk and failure assumptions. In addition to desktop analytical methods, it is recommended that empirical data be collected as part of an experimental project phase to reinforce assumptions related to ice jams, ice scouring, armor resilience and repair capabilities.

Predictive analysis of hypothetical system reliability and availability performance is evaluated through the construction of a system reliability model. The analysis uses statistical methods to produce model-based predictions for river-laid fiber cable failure. In addition to system reliability, which is directly tied to failure performance, system availability is also computed by modeling repair of the system following a failure event using operational repair assumptions.

The analysis shown in this study limits the scope to the in-river cable reliability and availability. Although the transmission equipment and facilities contribute to system unavailability, the failure and repair performance of power, facilities and transmission equipment are an order of magnitude or more greater than that of the predicted in-river cable performance. Furthermore, any lack of failure performance in power, facilities and transmission equipment can be mitigated through the use of additional redundancy or higher performing alternatives. The cable itself represents a unique and challenging system element that has few options when an increase in reliability or decrease in time to repair is necessary to achieve the target performance.

As is discussed below, even under the relatively conservative assumptions presented here, none of the communities passed achieve the target availability performance. This outcome should serve as an indicator that construction of a Kuskokwim River fiber system should only proceed with caution. The computed performance values are not so low that construction is not feasible. Rather, they're on the boundary of what would be considered acceptable. That boundary level of predicted performance along with the absence of significant empirical data related to ice jam to scour correlation and ice scour to cable break correlation increase the overall project risk, especially in the early years of operation.

Establishing a performance target for the system

The system reliability model is comprised of a hierarchical series of components that are analyzed as a group by cascading the reliability (or availability) contribution of each element. This method of modeling is referred to as the reliability block diagram approach. The reliability model used for the river system consists of three primary system components; the transmission system, the facilities, and the river-laid cable.

The analysis uses target performance levels that are established prior to performing the analysis. The subsequent analysis is then used to determine whether the target availability and reliability values would be practically achievable within the given constraints and risk profile. The overall system availability objective is set at 99.8% for the end-to-end system. This represents a value on the low to modest end of carrier-grade telecommunication operator expectations[1]. The lowered expectations are selected to accommodate the relative lack of maturity and operational

[1] Most telecommunications system of this type operating over terrestrial paths would be expected to achieve 99.95% or greater availability in the absence of redundancy. An availability of 99.95% is achievable with an expectation of one failure every 2 years and a mean time to repair of 8 hours.

knowledge inherent in a new system when first deployed. It is expected that once mature operational processes and methods are achieved the availability target should be increased to >99.95% for long-term operational expectations. Table 1 shows the system target availability, the associated annual downtime and the system life downtime.

Table 1. Kuskokwim River end-to-end availability target and associated downtime

Performance Metric	Value
Target availability	99.8%
Annual downtime	17.5 hours
System life[2] downtime	18.3 days

Using the data in Table 1 along with a set of assumptions related to transmission system and facility failure and repair performance, the required availability of each sub-component in the reliability block diagram chain can be computed. The transmission system and facilities are assumed to each have a minimum availability performance of 99.99%. This target (colloquially referred to as “four nines”) represents carrier grade telecommunications performance and inherently implies high quality design, redundancy, resilience and operational maturity. The assumed mean time to restore (MTTR) for electronics and facility systems is 6 hours. Use of a 6-hour MTTR value implies the presence of remote hands or staff capable of basic troubleshooting within each community where transmission equipment and facilities are present. These values represent operational expectations for long-haul middle mile fiber systems deployed in rural Alaska.

Table 2. Transmission and facilities availability target and allowable downtime

Transmission System / Facility Metric	Value
Target availability	99.99%
Annual downtime	0.9 hours
System life downtime	21.9 hours
Mean time to restore	6.0 hours
Required MTBF	240,000 hours

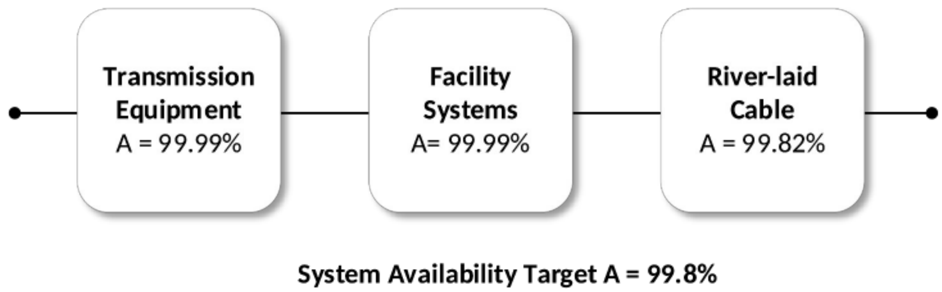
The unavailability due to cable failures to be computed using the end-to-end, transmission and facilities availability targets.

Table 3. Kuskokwim River in-river fiber cable availability and downtime allocation

Fiber Cable Metric	Value
Availability allocation	99.82%
Annual downtime	15.8 hours
System life downtime	16.4 days

[2] System life is assumed to be 25 years for the purposes of the analysis.

Figure 1. Kuskokwim River fiber optic cable system reliability block diagram



Modeling the in-river cable reliability

The in-river cable failure model simulates lifecycle performance to determine whether the target availability and reliability performance can be achieved. The model makes use of the linear regression ice jam results from the route selection, self-burial and ice jam section of this study. The ice jam model is used to approximate the annual occurrence of ice scouring within each river reach. The annual per reach ice jam probability is restated in Table 4 along with a column indicating which communities lie within a given reach. The cable breakage model along the river is cumulative. That is, the path from Aniak to Chuathbaluk, spanning only one reach is intuitively much more reliable than the path from Aniak to McGrath, which spans all river reaches. In the McGrath case the reliability of the cable is dependent on failure free performance of all 18 reaches.

Table 4. Annual ice jam occurrence probability by reach

Reach ID	Community	Jam probability
1	Aniak / Chuathbaluk	0.44
2		0.13
3	Napaimute	0.08
4		0.37
5	Crooked Creek	0.30
6		0.33
7	Red Devil	0.52
8	Sleetmute	0.35
9		0.38
10	Stony River	0.36
11		0.37
12		0.43
13		0.40
14		0.52
15		0.75
16		0.07
17		0.21
18	McGrath	0.40

Cable failure within a given year is approximated using the product of three random variables:

$$P_{failure} = P_{\text{ice jam}} * P_{ice\ \ scour} * P_{cable\ \ failure}$$

The annual probability of an ice jam for each reach is shown in Table 4. The probabilities used for ice scouring and cable breakage (armor defeat) are difficult to bound analytically due to the lack of empirical data. For this reason, a sensitivity analysis is performed to evaluate a range of possible reliability outcomes by varying the values of ice scour and cable failure probability over a range. This provides insight into which variables might be changed or optimized in order to achieve the required performance. The probability of ice scouring given an ice jam event is evaluated at values of 10%, 25% and 50% and reflect low, moderate and high likelihood outcomes. Ice jamming is correlated with ice scouring of the river bottom but objective, empirically supported data relating the percentage of cases in which an ice jam leads to a bottom scouring event was not found by the project team. The probability that the armor is effective in a scouring event is varied from 0 – 100% where 100% implies certain failure and 0% implies perfect reliability. It is believed that armor offers some level of protection[3] from scouring but, as in the ice jam to ice scouring causality case, data demonstrating the effectiveness of the armor in this specific environment and under these conditions was not found by the project team.

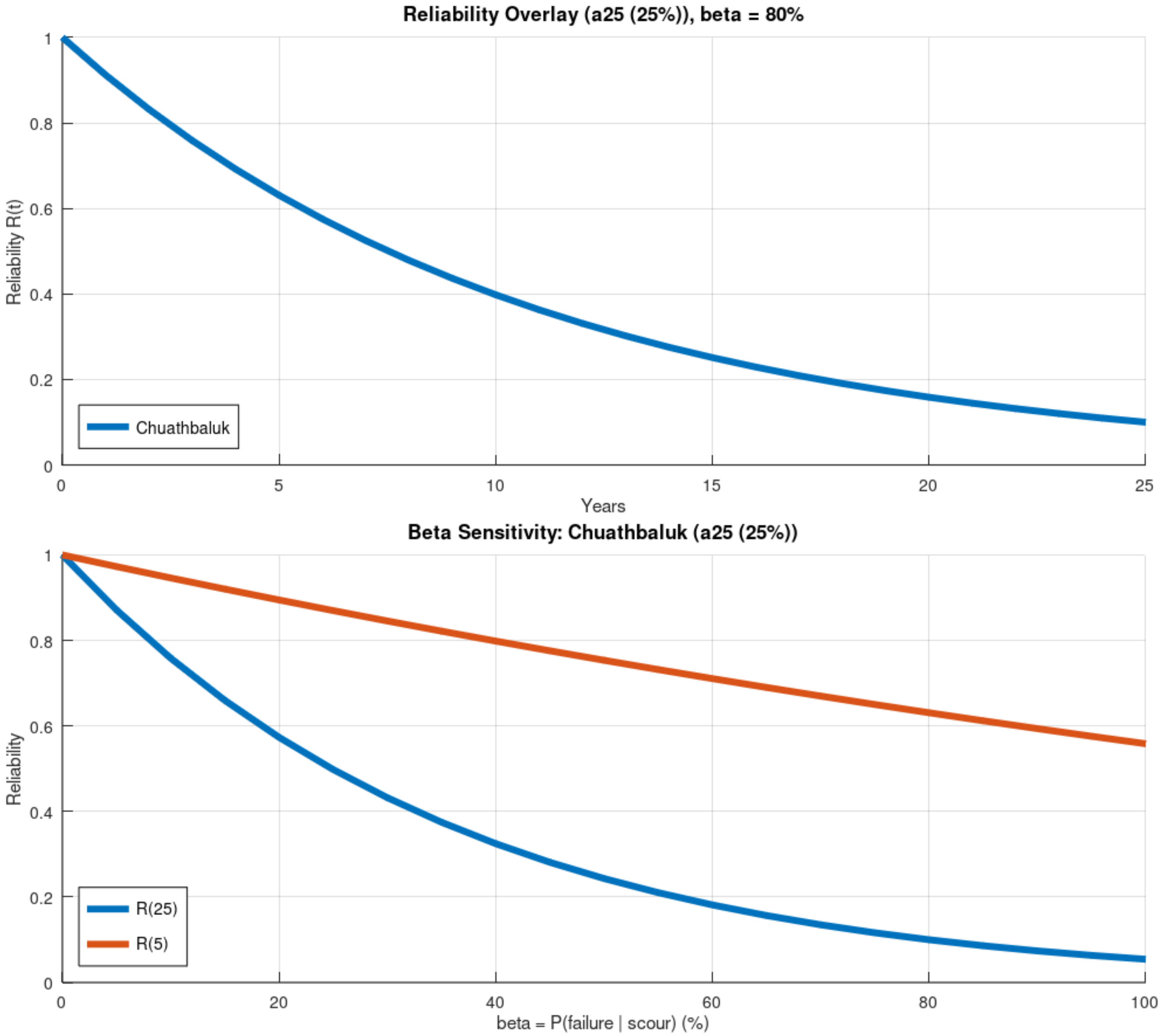
Cable reliability[4] results

Reliability in system life modeling is defined as the probability that a system survives for a stated period of time. The cable model is used to compute the reliability for each community as a function of time from system commissioning (t = 0 hours) to the end-of-life (t = 25 years).

[3] Two types of cable armor are generally used in submarine fiber systems. These are single and double-armor cable sheaths. Double armor is inherently more resistant to damage but the increased effectiveness should be quantified experimentally.

[4] Cable reliability in this model is limited to ice jam and scour events. Cable failures also occur due to anchor and bottom dragging from vessels in the river. Addition of this factor would serve to lower the computed reliability performance. It is not necessary or useful to include this factor as the results as shown demonstrate that target performance is not achieved without contributions from anchor or bottom drags. Finally, anchor and bottom dragging events are expected to occur during ice free seasons, which implies that the cable would be fixable within a much shorter time window and under more controlled circumstances.

Figure 2. Chuathbaluk reliability function and cable armor failure sensitivity

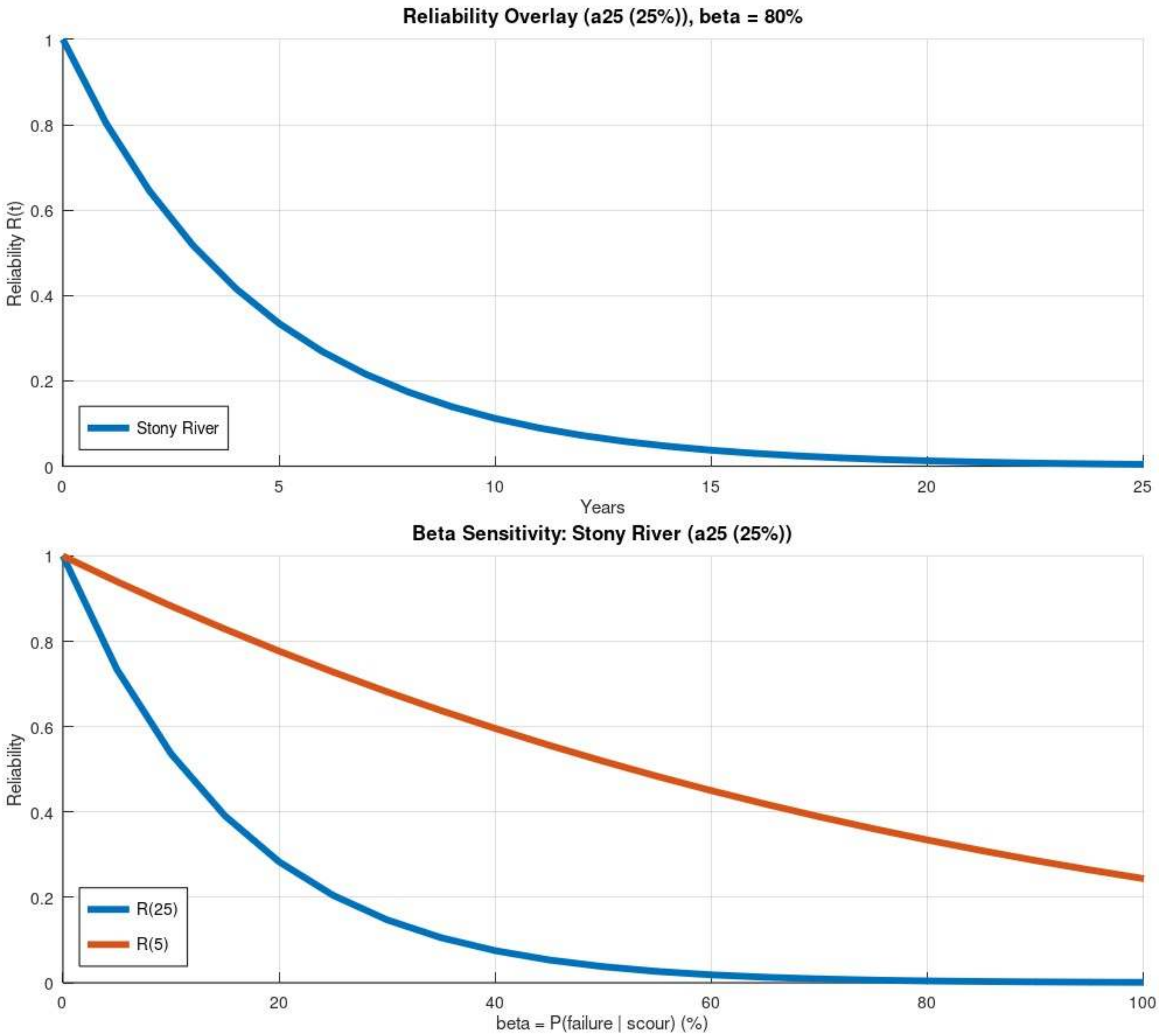


The data in Figure 2 assumes that in 25% of ice jam cases, scouring occurs. The top figure shows the reliability function for cable failures in 80%[5] of scouring cases. The bottom figure shows the sensitivity of the 5 and 25-year reliability to armor failure likelihood (with 0% representing perfect armor).

The 5-year reliability for the Aniak to Chuathbaluk link under these conditions is always greater than 60%, even under the worst-case condition where the cable fails in all ice scour circumstances. Shifting the view further upriver to Stony River, the performance is noticeably worse. Figure 3 shows the same charts for the community of Stony River.

[5] Armor is inadequate to protect the cable from scour in 80% of cases.

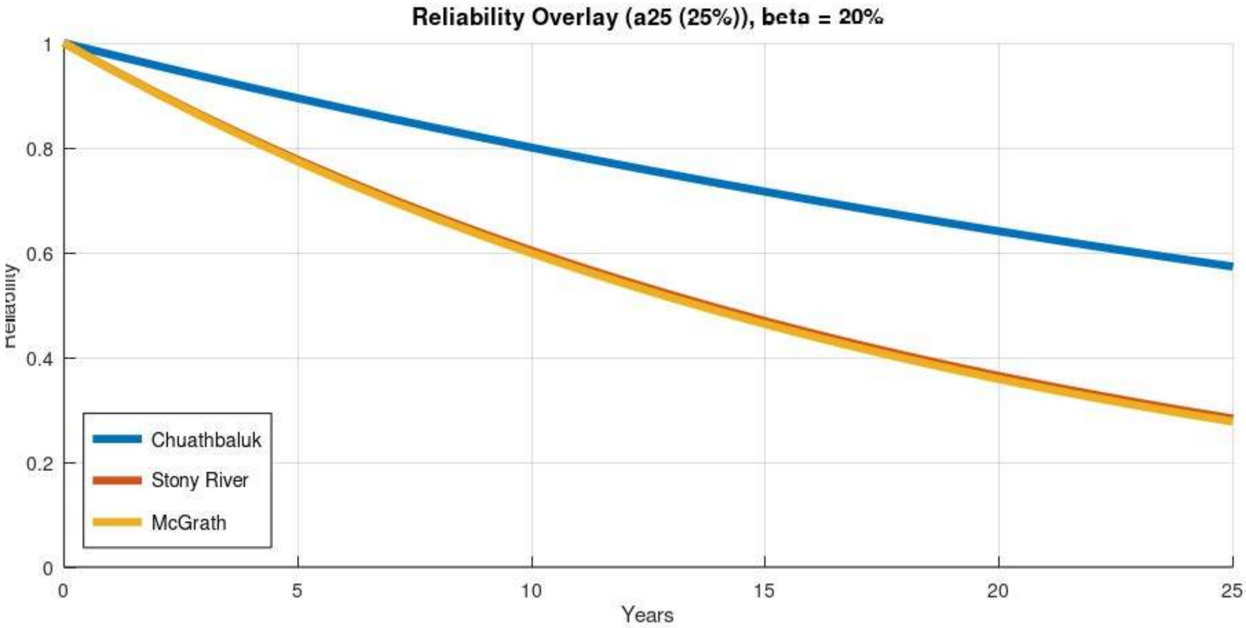
Figure 3. Stony River reliability function and cable armor failure sensitivity



The 5-year reliability for Stony River drops below 30% and at least one failure is certain unless the ice scouring failure occurrence rate can be limited to less than 50%. It should also be mentioned that once the cable distance reaches Red Devil, multiplicative accumulation[6] causes the reliability functions to effectively converge on the same value for all distances beyond Red Devil. Figure 4 provides a graphical representation of this behavior.

[6] The probability of failure on the river corridor is the product of the individual reach failure probabilities. Accumulation occurs as the products mount. Said in conversational terms, the likelihood that at least one ice jam (and thus ice scouring and cable failure come into play) occurs approach unity as Red Devil's distance is approached.

Figure 4. Reliability convergence between Stony River and McGrath



The reliability function is related to the failure rate by the expression:

$$\lambda = -\ln\left(1 - q_{fail}\right)\ \ failures\ /\ hour$$

where:

$$q_{fail} = p_{ice\ \ jam} * p_{ice\ \ scour} * p_{cable\ \ failure}$$

The failure rate of the system (λ) is assumed to be constant in time[7]. Telecommunications systems frequently use the Mean Time Between Failures (MTBF) as a figure of merit for system failure performance, particularly when availability is of interest. The MTBF of a system with a constant failure rate is expressed by:

$$MTBF\ =\ 1/\lambda$$

The MTBF for each community is computed for a probability of scour following an ice jam equal to 25% and a probability of cable failure given a scouring event equal to 80%. These assumptions result in the MTBF values shown in Table 5. The MTBF value reaches a floor of 5 years based on the assumption that the cable will fail 80% of the time when ice scouring occurs.

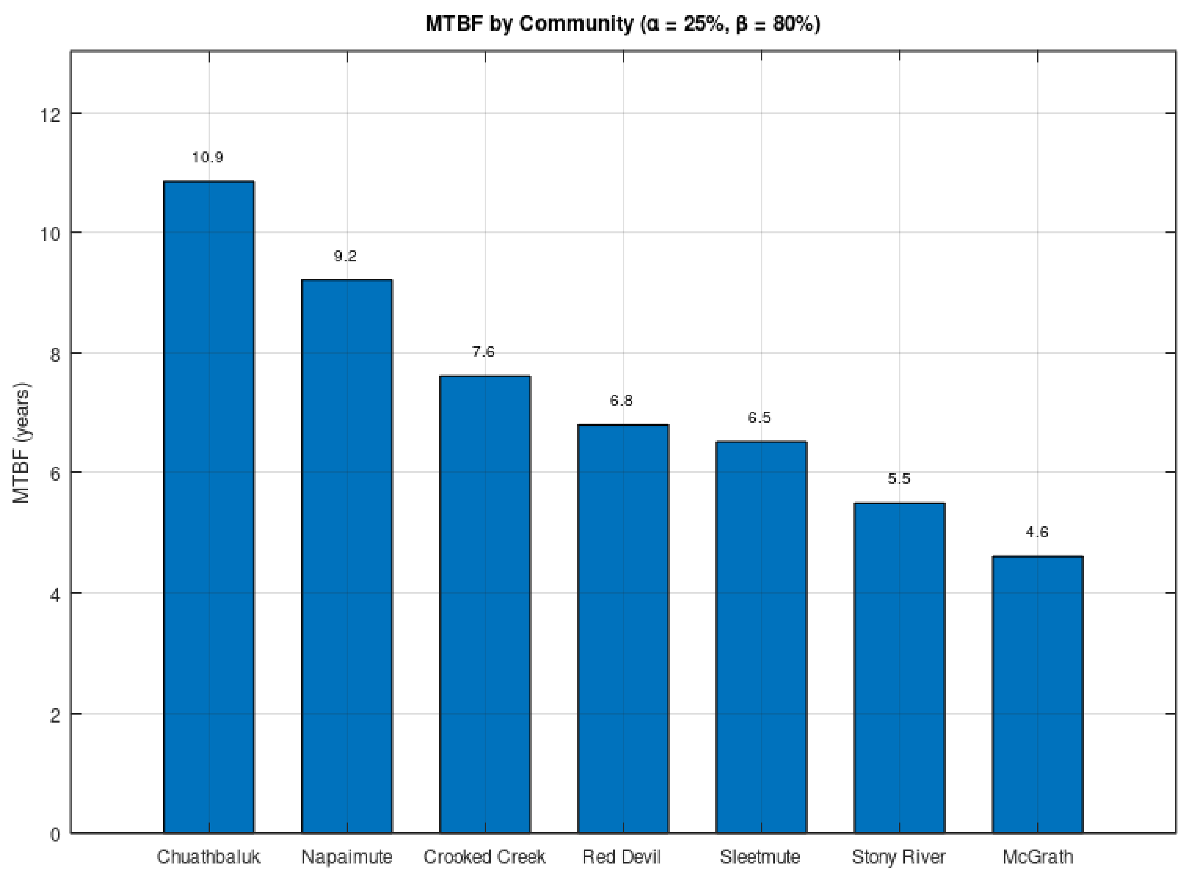
[7] It is common to assume that the failure for telecommunications system is constant with respect to time. In this case the simplifying assumption is used to allow insight into system behavior without overcomplicating the cable failure model. A real, river-laid cable system would have a failure rate that varied with time due to environmental, climate and hydrological changes that occur continuously in the river. The values computed represent steady-state, long-term performance and neglect transient river behaviors.

Table 5. Estimated failure rate and MTBF value by community passed

Community	Distance from Aniak (km)	Reach failure P	Failure rate λ (1/yr)	MTBF (years)
Aniak	0.0	0.000	0.000	∞
Chuathbaluk	18.1	0.440	0.088	10.9
Napaimute	53.1	0.514	0.103	8.6
Crooked Creek	112.1	0.616	0.123	5.7
Red Devil	167.3	0.684	0.137	4.8
Sleetmute	182.8	0.711	0.142	4.7
Stony River	231.7	0.832	0.166	4.6
McGrath	446.4	0.975	0.195	4.5

A chart of the MTBF by community is shown in Figure 5. It is noteworthy that in the model created, Stony River and McGrath have an MTBF value that is approximately half that of Chuathbaluk and Napaimute. Furthermore, as the probability of ice jam occurring between the community of interest and Aniak approaches unity, the MTBF value is driven entirely by the assumptions used for ice scouring and armor effectiveness. This implies that the collection of empirical data establishing a clear correlation between ice jams and ice scouring and the effectiveness of cable armor in resisting ice scouring is an important element of future work.

Figure 5. Kuskokwim River reliability model MTBF by community passed



Modeling the repair of a damaged in-river cable

Availability is the most ubiquitous metric used in characterizing the operational performance of telecommunications systems. System availability is reliant on both the frequency of system failures and the time it takes to place the system back into operation following a failure event (time to repair). One of the most fundamentally challenging aspects of evaluating the feasibility of operating a hypothetical fiber system in the Kuskokwim River is characterizing and quantifying the time to repair of a cable due to the presence of ice. The repair model used is segmented into two different failure scenarios. The first failure scenario is a fall season "ice formation" event. The second failure scenario occurs during the spring break-up season. Each scenario carries a different seasonal calendar of occurrence and time to repair. The time to repair is modeled as a random variable that allows the model to present a range of availability values with mean, median and standard deviations. The assumptions below are stated to justify and substantiate the suggested repair and recovery methods that follow.

- It is assumed that the cable is placed in the thalweg during installation and that some level of self-burial occurs as time elapses.
- During cable construction the installation team will map and document placement depth, particularly in shallow[8] areas.
- An Electronic Marker System (EMS) is used during shallow-water cable placement to ensure recovery of the cable following a fault is possible. Shallow water cables can often be located by injecting a 25 kHz tone over the metallic buffer tube. This provides a typical location range of 50 km from the injection point. Use of copper buffer tubes can extend the range to approximately 100 km.

Cable repair during the fall season

Failures occurring in the fall ice formation season are treated with a two-stage repair model. A deep water cable break is proposed to be repaired through the use of a temporary cable. This cable is interconnected with the unbroken cable at the nearest shallow water recovery point both north and south of the cut. The assumptions and associated logic for a simulated fall season repair are outlined below.

- The outage is modeled as persistent until ice is safe for river travel and work to occur. This date is assumed to be December 15th.
- The location of the nearest shallow water points north and south of the break are identified using as-built location and depth records.
- The cable is recovered using a combination of EMS, OTDR and as-built maps. The ice is excavated at each end and the cable is recovered.
- A temporary cable is spliced between the north and south ends and placed on the ice surface. The surface-laid temporary cable is marked at regular interval to minimize the likelihood of river vehicular traffic damage.
- Service is re-established until spring break-up at which time another failure is expected to occur as the ice breaks up.
- Permanent repair is performed following ice-free river conditions and the temporary cable splice is removed.

Cable cuts occurring in shallow water follow a repair process identical to the deep water repair with minor changes to avoid the spring break-up failure. The actions outlined below only apply in

[8] For the purposes of this discussion "shallow" refers to a river depth of 6 feet or less.

conditions where a permanent repair is deemed feasible during fall events. In the absence of permanent repair confidence, the deep water repair methods above are used.

- If the cable is determined to be in water at a depth of 6 feet or less, all feasible methods should be explored to find the actual location of the fault.
- Depending on the length of the damage a trench might be cut, or a hole opened where slack is pulled through to allow for the damaged section to be removed and replaced with a new, armored section of cable.
- All fall season failures are modeled to occur between the dates of November 1st and December 1st. The time between shore-fast ice and fully frozen river conditions is assumed to be the most volatile. Failures within the fall season are uniformly distributed between November 1st and December 1st.
- Following a fall season failure, the temporary surface-laid repair is modeled as a Normal random variable with an average of repair time of 10 days (including logistics, field deployment and actual repair) with a standard deviation of 3 days. No repair takes less than 5 days to complete.
- Temporary repairs are expected to experience a subsequent failure in the spring when break-up occurs. This failure is modeled to occur within the spring break-up window of April 20th and May 7th. The downtime is modeled as the sum of the time it takes to perform the permanent repair and the time elapsed between the temporary cable being cut due to ice movement and ice-free river conditions occurring. Spring break-up should be carefully monitored as ice break-up could capture the surface-laid cable and carry it downstream, complicating the permanent repair.

The fall season downtime is expressed numerically as:

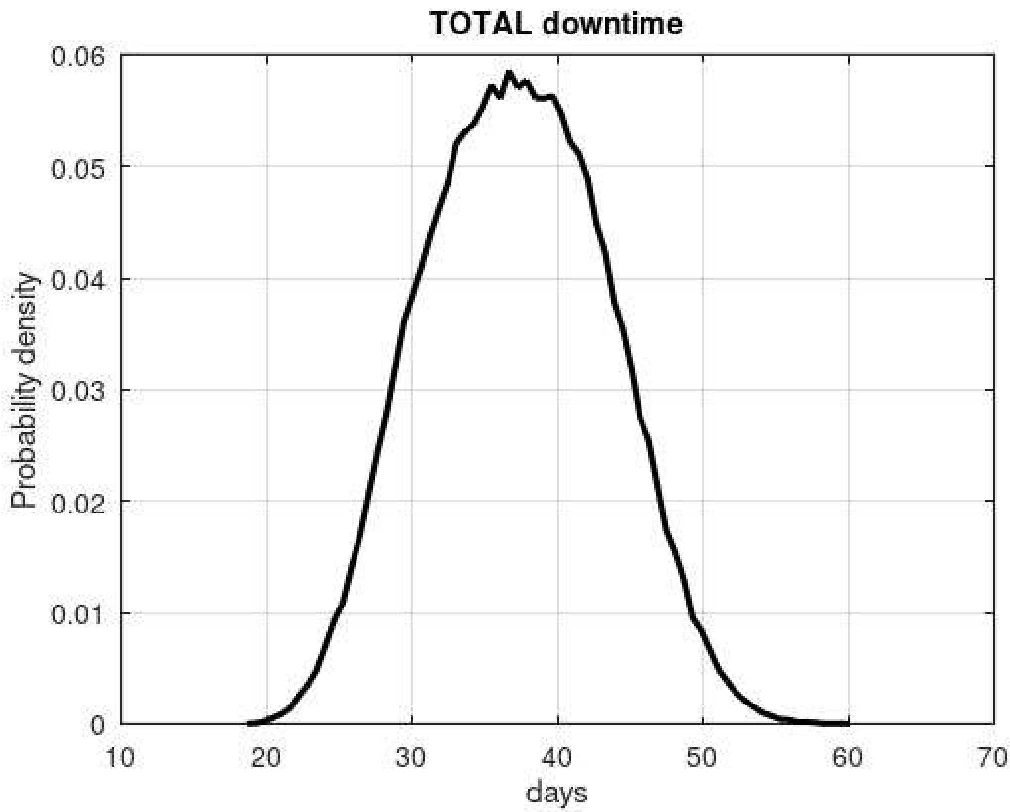
$$D_{fall} = D_{temp} + D_{perm} + D_{break\text{-}up}$$

Where the total downtime is the sum of the time it takes to make the temporary repair, the time it takes to make the permanent repair and the time elapsed following the spring break-up failure.

$$\begin{aligned} D_{temp} &\sim N\mathrm{ORM}(10,3) \text{ truncated to } > 5 \text{ days} \\ D_{perm} &\sim N\mathrm{ORM}(10,3) \text{ truncated to } > 5 \text{ days} \\ D_{break\text{-}up} &\sim UNIF(April\ \ 20,\ May\ \ 15) \end{aligned}$$

Figure 6 shows an empirical probability density function for fall season cable repairs. The downtime associated with fall season repairs are Normal distributed events that are shifted in time based on the outage experienced in the spring associated with a repeated failure when break-up occurs.

Figure 6. Fall season cable failure time to repair estimate



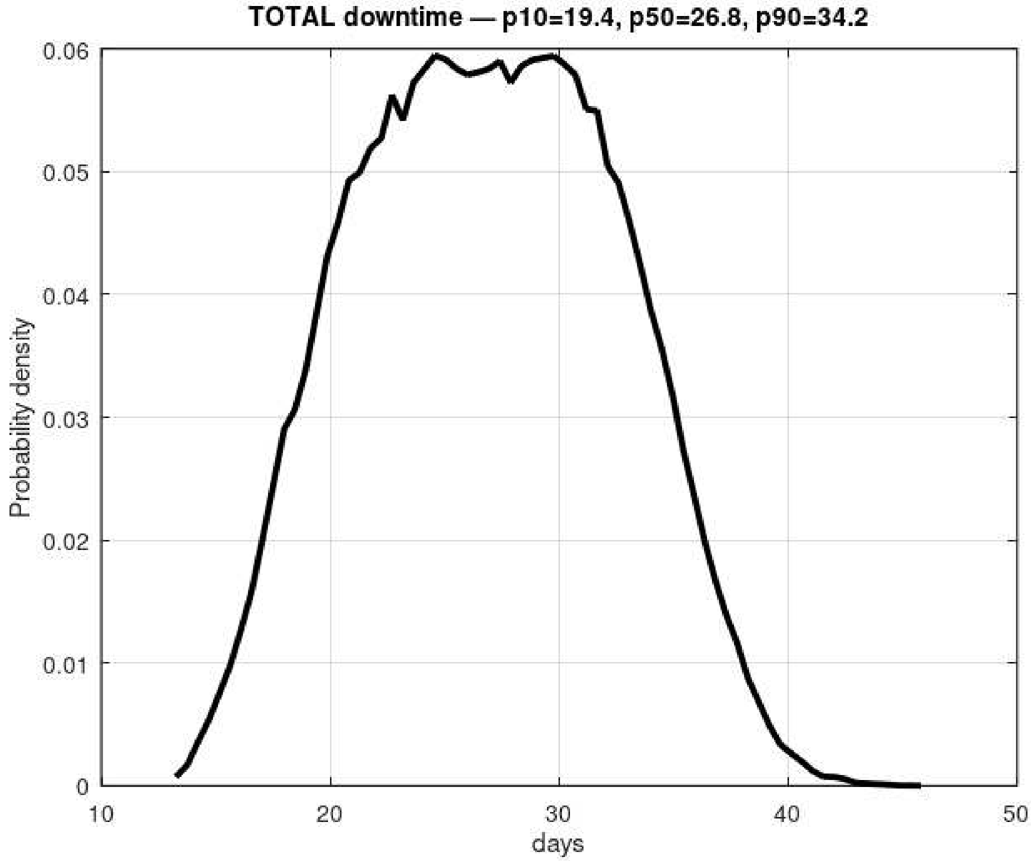
Failures during the spring break-up season

Failures occurring in the spring season are modeled using the same methodology as those occuring in the spring season, but without the temporary repair event prior to the permanent repair. In spring failure instance the downtime is modeled as:

$$D_{spring} = D_{perm} + D_{break\text{-}up}$$

Where the repair and break-up downtimes are the same as those modeled in the fall event case. Figure 7 shows the empirical PDF of the spring season downtime.

Figure 7. Spring season cable failure time to repair estimate



Modeling the split of fall and spring season failures

System availability is computed by defining occurrence distributions associated with the fall and spring season events. These events are used in Monte Carlo simulations which use three different splits of fall and spring failure occurrence.

Table 6. Fall and spring season repair sensitivity analysis assumptions

Fall Events	Spring Events	Mean Downtime	P10%	P90%
20%	80%	27 days	19 days	34 days
50%	50%	32 days	21 days	43 days
80%	20%	35 days	26 days	44 days

System availability estimation

The fiber-optic cable availability is computed using the failure rate and repair models detailed above. The cable availability is presented as a statistical distribution of possible outcomes. The availability to each community is shown in Figure 8 along with the target cable availability from Table 3 of 99.82% availability. Under the assumptions presented in this document, none of the communities achieve the target availability. Furthermore, as the distance from Aniak increases, the variation in expected performance increases as well. Tighter control on assumptions will improve accuracy but is not expected to cause the availability to drift to the level of the target performance goal.

Figure 8. Mean cable availability model by community for three hybrid fall / spring repair splits