Kuskokwim River Middle Mile Fiber Technical Feasibility Study

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Arctic River-laid Cable Instrumentation

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Introduction

The primary reliability concern associated with the operation of a fiber-optic cable placed within the flowing waters of the Kuskokwim River is cable breakage. Cable breakage is most likely to occur during seasonal ice-formation and break-up. Cable repair during these two seasons represents significant logistical challenges should a failure occur as the formation or presence of ice in the river restricts or prohibits any repair activity. Recent off-shore failure events on Alaska's North Slope[1] have led to justified concern and skepticism with regard to the feasibility and practicality operating fiber optic cables in Arctic waters.

Management of cable breakage risk relies on achievement of two major operational goals. The first operational goal is system visibility. Telecommunication operators invest a significant amount of time and resources into the ability to monitor and effectively operate their networks. Network visibility provides insight into system health and network performance. In the case of a river-bottom laid cable, the ability to observe cable stress or strain prior to breakage is an important component of preparing for a restoration prior to the event causing service-impacting downtime. The second operational goal, discussed in the installation means and methods and reliability sections of this study is the ability to repair the cable following a breakage event. Methods are suggested to facilitate cable repair under ice covered conditions.

Detecting the presence of cable strain

Fiber breakage risk in the case of the Kuskokwim River is assessed through a multi-layered approach. The risk of ice jam formation and subsequent ice scouring events is modeled in the "Route Selection, Self-Burial Assessment and Ice Jam Risk" section of this study. The impact of those modeled behaviors are used in the reliability analysis to estimate the mean availability and reliability performance of a river-laid cable system. Use of BOTDR instrumentation increases the chances of observing degraded or failure-prone conditions prior to a total system failure. This, in turn reduces the overall time to restore for a cable, assuming that repair methods are in place to take action prior to the event occurring.

Preliminary risk assessment

System risks can only be managed effectively if they are well understood. To this end, the study team has gathered a wide variety of data in order to estimate the likelihood of ice jam formations along the river between Aniak and McGrath. The ice jam probabilities are assumed to be highly correlated with ice scouring events. The correlation of ice jams within the river corridor leading to ice scouring and the scouring ultimately leading to a fiber cable break is an emerging area of study in river-laid cables. The relationship between sediment type, cable self-burial depth, river sinuosity (and braidedness) and scour event breakage requires empirical field data to validate desktop analysis results. In the absence of this validation, this report asserts that a higher likelihood of ice jams will be proportional to a higher likelihood of fiber cable breakage. Identification of the highest risk areas within the river allows the design to focus mitigations within target reaches.

Risk minimizing design basis

The river-laid cable design consists of several primary elements intended to increase cable survivability. These elements include the specification of cable armor and coating(s), the exploration of under-ice repair methods, and placement of vaults and handholes to allow for

[1] https://mustreadalaska.com/breaking-quintillion-fiber-optic-cable-is-broken-again-on-north-slope-and-northwest-alaska/

terrestrial “route around” during failure events. Areas of highest risk with silty or sandy river bottom sediment composition might be expected to experience self-burial and thus not justify the placement of double-armor. Industry observations indicate that the increase weight and size of double-armored cables can lead to faster and deeper self-burial behavior. River bottoms of bedrock composition would not be expected to self-bury the cable and, when combined with the presence of a high likelihood of ice jam behavior, double-armoring should be considered.

In addition to cable armor, the formation of frazil ice is a risk that leads to cable floatation. Cable floatation represents a significant risk for cable breakage as the cable becomes suspended in the water column and interacts with moving river elements (ice, rocks, trees, etc.). Methods to mitigate frazil ice cable floatation include the encouragement of self-burial behaviors and the placement of frazil resistant coatings or jackets (HDPE) on the cable sheath itself to minimize the likelihood of frazil ice adherence to the cable.

Reduction of cable breakage risk is bolstered by a strategy to also provide rapid-restoration capabilities should an actual breakage event occur. Planning for rapid-restoration requires carefully placed fiber vaults and cable spools in order to facilitate on-shore fiber placement while break-up or winter elapses. Once the river is open and repair becomes possible, the temporary fiber can be respooled and replaced for future use. This mitigation, although expensive, is deemed an almost certain requirement in order to provide assurance that long-term outages are avoided. An alternative method to longer vault-to-vault restorations is the exploration and refinement of under ice cable recovery and repair. In that scenario, the cable would be recovered in shallow areas north and south of the cable breakage point (identified using OTDR[2] methods). Once the cable is recovered and on top of the ice surface, the cable would be temporarily spliced to an armored surface laid cable until the spring when a full repair could be made. The under ice repair scenario is not practical during the break-up season as the ice is unsafe for human access. Rather, this scenario becomes important should a fall ice-formation event lead to a cable breakage. In that case it substantially reduces the duration of an outage.

Pro-active cable health monitoring using BOTDR instrumentation

The final component of arctic river-laid fiber system risk minimization involves instrumentation and pro-active monitoring of the fiber cable’s physical condition. Specifically, currently available Brillouin Optical Time Domain Reflectometry (BOTDR) technology allows fiber segments to be monitored for strain conditions in reach lengths of approximately 100 km or less. Within each <100 km reach, the system measures and records the presence of fiber strand strain. Strain is defined as the deformation of the cable along its longitudinal axis. It can be assumed that strain within the fiber system is due to presence of external forces and that increasing strain would logically lead to a cable failure. These measurements, when coupled with the downtime mitigations discussed, allow telecommunications system operators to build operational plans for the system that lead to higher availability for broadband system end users.

BOTDR strain measurement theory

Strain is the physical deformation the glass fiber inside a fiber optic cable bundle. This strain can be manifested as stretching, compression or bending. Strain is expressed mathematically as a dimensionless measure. In the context of fiber optic cables the term microstrain ($\mu\epsilon$) is often used and refers to microns of strain per meter of length.

[2] OTDR refers to Optical Time Domain Reflectometry, a measurement technique where the location of a cable fault is identified by sending optical signal pulses through the cable and measuring the elapsed time to a received reflection of the transmitted signal.

$$strain = \frac{\Delta L}{L}$$

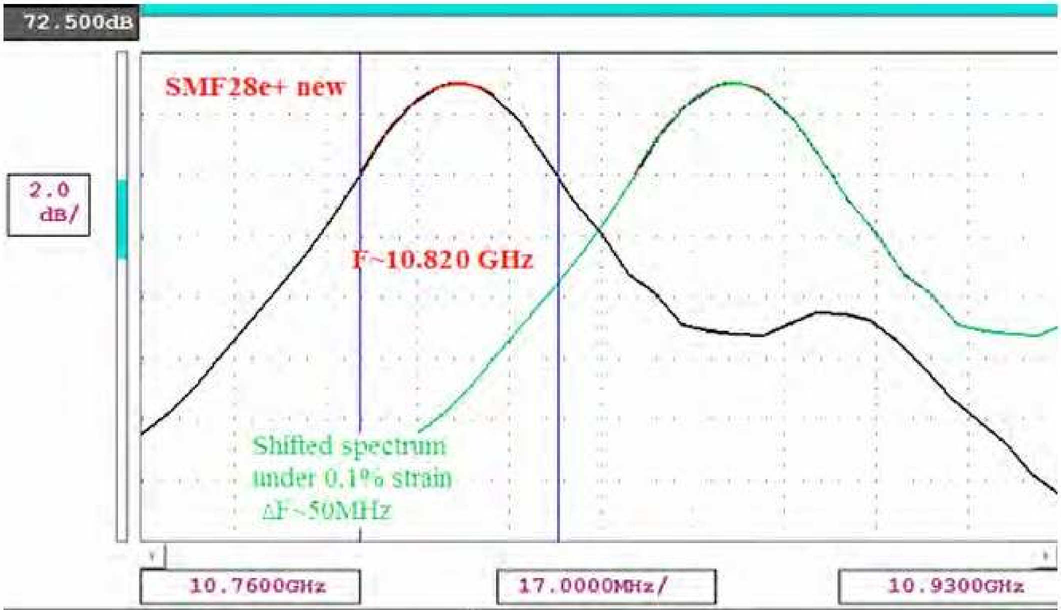
Where L is the length of a cable segment and DL is the change in length. Strain in a fiber optic cable can be caused by a number of physical processes within the river. These include the formation of ice around the cable, pressure exerted on the cable due rocks or ice settling on the cable and tension applied to the cable cause by pulling forces.

All of these mechanisms can be observed remotely using a technical called Brillouin Optical Time Domain Reflectometry (BOTDR). Standard Optical Time Domain Reflectometry (OTDR) has been available in the fiber optic industry for decades and is regularly used to identify the location of breaks and faults in fiber systems. BOTDR systems differ from standard OTDR systems in the interpretation of the reflected spectral response[3]. Fundamentally, the Brilluion backscatter signal is frequency shifted by the presence of strain in the fiber strand. This frequency shift can be accurately correlated to a physical deformation and thus the amount of strain present is characterized. Fiber optic cable types (G.652, G.654, etc.) produce different spectral signatures, but all cables produce a predictable frequency shift when exposed to strain.

Brilluion frequency shift is also sensitive to changes in the fiber temperature. This temperature sensitivity allows differential changes in the ambient water temperature of the river to be measured and cataloged[4]. Figure 1. shows a Brilluion backscatter spectrum response taken from an SMF-28e+ low loss optical fiber (Corning WP4259).

[3] See Corning WP4259 – BOTDR Measurement Techniques and Billuion Backscatter Characteristics of Corning Single-Mode Optical Fibers.
[4] These temperature measurements, although not precise enough to predict ice jam build up, could be of particular interest to fish habitat and river resource researchers.

Figure 1. Brilluion SMF-28e+ backscatter response showing 0.1% cable strain



Commercial BOTDR Systems

Brilluion OTDR systems are commercially available from a number of vendors. These systems are most frequently used in pipeline, power grid, energy and civil infrastructure applications. Use of BOTDR systems in telecommunications applications is primarily limited to submarine cable systems but their use in those applications is somewhat limited due to the relatively short reach of BOTDR measurements (<100 km). This limits submarine use to near-shore applications. The Kuskokwim River project is a unique opportunity to apply this technology and integrate it into telecommunications operations where pro-active monitoring and fault mitigation are a fundamental component of the system. A review of the commercially available systems reveals at least three options exist with the potential for direct deployment on the Kuskokwim River. A summary of the available features and capabilities is shown in Table 1.

Spatial resolution refers to the segment over which the measured strain occurs. On longer systems such as the one proposed for the Kuskokwim River cable, this spatial resolution (or gauge length) is approximately 3.0 – 10.0 meters. Within that spatial resolution range the strain present is represented by the strain measurement performance in microstrain. As an example, in a 50 km BOTDR span with a 5.0 m spatial resolution, the resolvable strain is approximately 0.05 – 0.25 mm of cable deformation *across the spatial resolution range.* Table 1 summarizes the relevant specifications for BOTDR systems as they apply to the Kuskokwim River cable system.

Table 1. Kuskokwim River BOTDR system feature table

Feature	Specification
Range	70-80 km
Spatial resolution	3.0 – 10.0 m
Stain measurement performance	10-50 $\mu\epsilon$
Data and logging	TCP / IP connectivity, SNMP, alarms

Cost	~$150,000 / interrogator

Kuskokwim River BOTDR system design

Deployment of a BOTDR system on the Kuskokwim River relies on the presence of regularly spaced intervals within the reach of BOTDR interrogators. Given the ~80 km limitation of the BOTDR devices, intermediate communities between Chuathbaluk and Stony River require the placement of cable vaults and identification of a location where instrumentation can be placed if landing shelters are not constructed in those communities. Table 2 shows the intermediate communities along the Kuskokwim River along with the distances between each community.

Table 2. Kuskokwim River route span distances between communities for BOTDR installation

Community A	Community Z	Distance
Aniak	Chuathbaluk	18.1 km
Chuathbaluk	Napaimute	35.0 km
Napaimute	Crooked Creek	59.0 km
Crooked Creek	Red Devil	55.2 km
Red Devil	Sleetmute	15.5 km
Sleetmute	Stony River	48.9 km
Stony River	McGrath	214.7 km

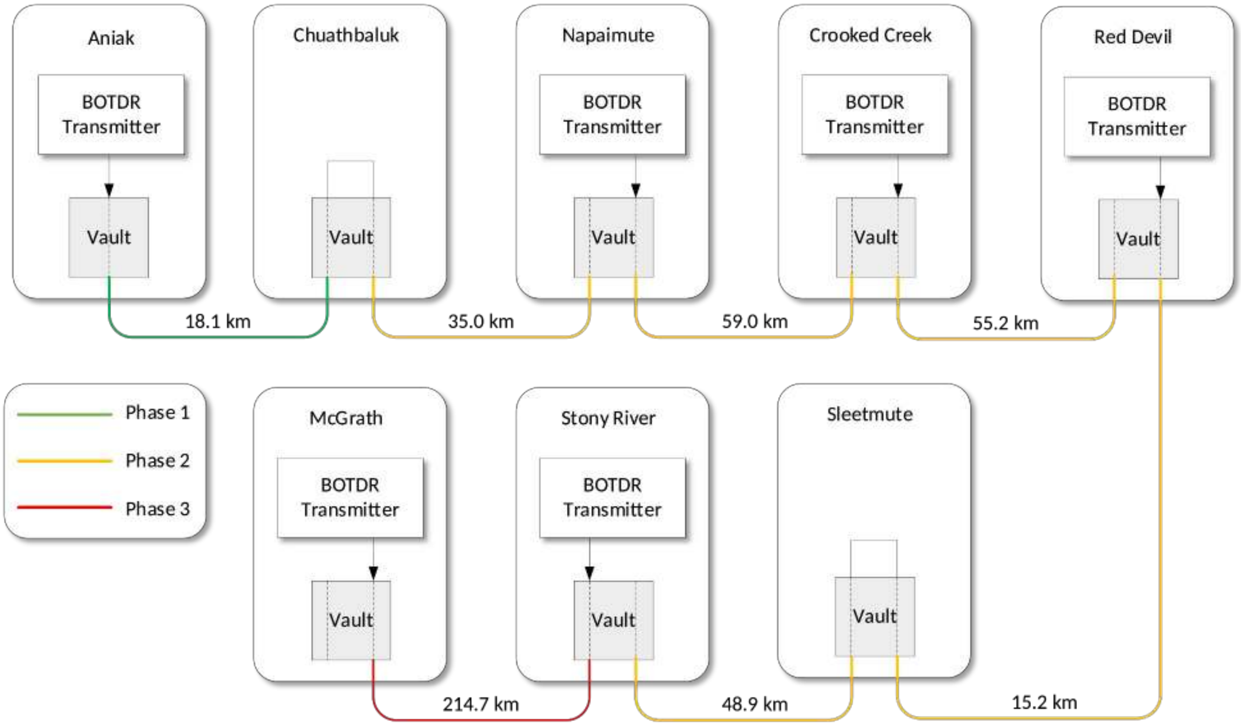
It is important to note that no permanently occupied communities exist between Stony River and McGrath. This fact introduces a risk to that segment of the path. None of the commercially available BOTDR systems have sufficient reach to characterize the path from Stony River to McGrath unidirectionally. The best compromise to serve this segment would be to deploy a unit in both Stony River and McGrath and point the systems toward each other. Even in that case, approximately 50 km of river is left unmonitored.

Table 3. Kuskokwim River BOTDR system installation locations

Community	BOTDR South	BOTDR North
Aniak	No	Yes
Chuathbaluk	No	No
Napaimute	No	Yes
Crooked Creek	No	Yes
Red Devil	No	Yes
Sleetmute	No	No
Stony River	No	Yes
McGrath	Yes	No

Table 3 provides a north / south view of the locations to install BOTDR functionality to ensure operational coverage of all river segments with the exception of the span from Stony River to McGrath. Figure 2 shows a graphical block diagram depiction of the BOTDR system with fiber routes colored by proposed project phase

Figure 2. Kuskokwim River BOTDR system design by project phase



The system shown in Figure 2 assumes that a BOTDR transmitter is installed in each community where a vault is placed with the exception of Chuathbaluk and Sleetmute which can be bypassed due to the reach of the BOTDR system.