2026 NDIA MICHIGAN CHAPTER
GROUND VEHICLE SYSTEMS ENGINEERING
AND TECHNOLOGY SYMPOSIUM
MODULAR OPEN SYSTEMS APPROACH TECHNICAL SESSION
AUGUST 11-13, 2026 - NOVI, MICHIGAN

ROBUST FIBER OPTICS FOR GROUND COMBAT VEHICLES: UNLOCKING THE BANDWIDTH FOR THE MISSION

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ABSTRACT

The U.S. Army's Modular Open Systems Approach (MOSA) is driving data-centric vehicle architectures that demand higher bandwidth, faster decision loops, and greater cross-platform interoperability. Despite these needs, stakeholders hesitate to adopt fiber optics because of perceived fragility, field-retrofit FOD risk, and soldier-handling concerns. This paper characterizes common fiber failure modes in ground-vehicle environments and demonstrates how system-level ruggedization, connector design, and qualified components mitigate those risks. Drawing on demonstrated experience with hardened optics, connector-integrated transceivers, sealed media converters, and rugged cabling, we summarize practical architecture and field maintenance procedures that enable reliable fiber deployment in vehicles. Results show that, with appropriate component selection, installation practices, and built-in diagnostics, fiber optics can provide a robust, maintainable backbone for future ground vehicle networks.

Citation: Heath Kouns, Marc Simms, Evan Weiss, Joe Breedlove, "Robust Fiber Optics for Ground Combat Vehicles: Unlocking the Bandwidth for the Mission," In *Proceedings of the Ground Vehicle Systems Engineering and Technology Symposium* (GVSETS), NDIA, Novi, MI, Aug. 11-13, 2026.

1. INTRODUCTION

Modern vehicles are becoming highly networked platforms, high-definition video, multi-sensor fusion, and semi-autonomous systems all demand an increased bandwidth, with lower latency, and a greater immunity to interference than legacy copper cabling can provide. Fiber optics delivers those capabilities (scalable data rates, lower weight, EMI immunity, no ground loops), but adoption in vehicle fleets has lagged because of worries about ruggedness, field handling, and sustainment.

That perception is increasingly out of date. Over the last decade physical-layer technology has been hardened for vehicle use: crush-resistant buffers (PEEK and similar materials), armor and aramid strength members, improved jacketing, faster field splices, and more robust termini. Mil-grade connectorization and proven sealing/packaging techniques and lessons carried over from aerospace, naval, and launch applications that make fiber viable in many vehicle locations. Practical maintenance tools and procedures have also matured, shortening repair times and lowering sustainment burden.

What follows catalogs the vehicle stressors that matter, shows where real failures originate, and outlines system-level ruggedization and architecture choices that let fiber safely replace copper in demanding ground platforms.

2. THE HARSH ENVIRONMENT OF GROUND VEHICLES

Ground combat vehicles put fiber-optic cabling and terminations through a unique mix of punishing conditions. Short, high-energy shocks from gunfire, blasts, or ballistic impacts can momentarily shift connectors or stress terminations, while continuous, broadband vibration from tracks, engines, and rough terrain slowly loosens hardware and fatigues cable jackets. Desert dust, blowing sand, and/or mud abrade ferrules and create contamination films that increase loss, especially during mate/demate cycles. Wide temperature swings and rapid heating or cooling induce expansion mismatches in metal, polymer, and adhesive bonds, degrading seals and stability over time. Coastal salt fog, humidity, and chemical exposure from fuels, hydraulic fluids, or cleaners can corrode, swell, or embrittle materials. Per MIL STD 810, these are realistic qualification concerns and should drive harness and connector design.

Mechanical abuse and routing stresses such as tight runs through turret rings and hinge lines , repeated flexing across service loops, stepping on harnesses, and pinch/crush events as a few examples,create microbend and macrobend losses through the optical pathway, or localized sheath damage, and compromised strain relief that often show up as higher attenuation with no obvious external damage, so diagnostics and fault isolation get tricky.

Field retrofits and human factors add a second failure mode: hurried mate/demate, FOD, and poor cleaning lead to contaminated or misaligned termini, which is the common root of the “fiber is fragile” perception, not brittle glass. Compared with copper, the failure modes are different: copper failures (broken conductors, shorts, visible crush) are usually obvious and electrical, but copper needs heavy shielding, grounding and is vulnerable to EMI and ground loop problems; fiber avoids those EMI issues and scales far better in bandwidth, yet is more sensitive to tight bends and end face contamination. With good routing, robust strain relief, sealed or expanded beam connectors, and simple field procedures, fiber’s hidden failure modes can be managed so the overall system is at least as rugged as an equivalent copper installation while keeping fiber’s bandwidth and EMI advantages.

3. THE REALITY OF FIBER-OPTIC ROBUSTNESS

Despite common perceptions, optical fibers deployed within ground vehicle harnesses are far more robust than often assumed. The core component, the glass fiber itself, is not prone to breaking as a brittle material under typical handling or operational stresses when properly integrated in a cable assembly. Instead, the predominant causes of optical link degradation stem from secondary effects such as microbends, contamination, insufficient strain relief, or connector retention failures.

From a mechanical standpoint, silica glass fibers exhibit extremely high tensile strength, often exceeding several gigapascals when free of surface flaws. The main vulnerabilities arise where stress concentrators occur like in situations with sharp bends, improper cable routing, or mechanical kinks that induce microbends causing localized scattering and attenuation without fiber fracture.

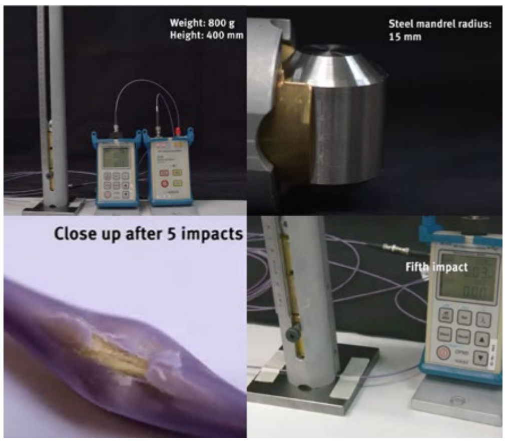

Figure 1 Impact Drop Test for Optical Fiber

Over the past 10+ years, the fiber optic cabling on the physical layer has become more rugged, with crush resistant PEEK inner layers for impact and handling protection. IEC 60794-1-2-E4 testing evaluates the mechanical impact resistance of fiber optic cables by subjecting them to multiple specified impacts. (see Figure 1) A typical test result shows that even after more than five impacts, which may cause visible damage to the cable's outer covering, the insertion loss of the optical fiber changes minimally, demonstrating the cable's ability to maintain optical performance despite mechanical abuse. Proper cable jacketing and the inclusion of strength members (e.g., Kevlar aramid fibers or steel-reinforced rods) are critical for absorbing tensile and compressive forces, protecting the inner glass core from direct stress and environmental damage. Advances in rugged repair/splicing technology has enabled field repairs with simple hand tools in under 30 minutes during deployment. Mil-spec connectors have continued to improve on the integration of fiber optics with new termini and interconnect technology designed to protect the fiber optic links in the vehicles.

Beyond mechanical resilience, fiber optics intrinsically offer several advantages critical for modern ground vehicle networks. They are immune to electromagnetic interference (EMI), do not generate ground loops, and lack conductive pathways, which eliminates common noise and signal integrity problems characteristic of copper cabling. Consequently, fiber optic links enhance electromagnetic compatibility (EMC) and support secure communication standards including TEMPEST and EMSEC, reducing the risk of signal eavesdropping and maintaining data integrity in contested environments.

These intrinsic benefits, however, can only be fully realized through system-level integration practices rather than relying solely on individual component robustness. Solutions must encompass ruggedized connector designs with secure retention and contamination mitigation, controlled cable routing with strain relief zones that respect minimum bend radii, and environment-specific jacketing materials. Combined with proper installation and maintenance procedures, these practices ensure reliable performance and long operational lifetimes.

In summary, optical fiber robustness in ground vehicles is a function of considered system engineering and deployment best practices, not simply material properties. Ignoring the system context leads to misconceptions of inherent fragility, whereas embracing the overall ruggedization unlocks the full value of fiber optic networks for demanding military applications.

4. RUGGEDIZED SOLUTIONS

Fiber optic networks have been around for decades and have been successfully adopted in harsh environment applications. To support this adoption, it became imperative to develop systems and components that withstand extreme environmental demands while maintaining consistent performance. Advances in material selection and protective packaging such as crush-resistant inner layers, bend-insensitive glass, and stronger outer jackets have substantially increased the mechanical durability of fiber optic cable assemblies. These advancements, combined with more durable connector solutions less prone to damage and foreign object debris (FOD) contamination, have made fiber optic networks more suited to military and aerospace environments than ever before. Nevertheless, many system integrators remain cautious, retaining the perception that glass fibers are inherently fragile. Even when the benefits of fiber optic links are compared over copper links, such as higher bandwidth, greater reach, and immunity to electromagnetic interference are understood, concerns about accidental damage or improper handling can delay adoption. Continued technical training, standardized handling procedures, and wider operational deployment can help dispel these misconceptions and remove barriers to adopting robust, modern fiber optic networks.

4.1. Expanded-beam Termini:

Expanded-beam termini and connectors are a proven, field-ready solution for deployable optical connections. Offered mainly as ball-lens (TFOCA II style) and GRIN-lens (38999/Micro38999 style) variants, these interfaces widen the optical aperture between mating elements so links tolerate particulate contamination and moisture far better than physical-contact end faces. That larger optical pathway simplifies cleaning (compressed air or simple wipes), reduces sensitivity to small misalignments, and extends service life across many mate/demate cycles, traits demonstrated in early rugged connector work such as the ROC design (see [3]). Tradeoffs include modestly higher insertion loss and larger form factors compared with polished-contact termini, but in exposed vehicle use the durability and maintainability of expanded-beam designs often outweigh those penalties. Figure 2 shows a typical expanded-beam terminations and a commonly fielded form factor.

Figure 2 Expanded Beam Termini

These connectors have been in use for decades and have a variety of form factors to suit the environment or operation they are performing. Some are designed for quick connect/disconnects for deployable instruments reducing setup time, while others can act as hybrid connectors carrying optical data and power through the same cable. The longevity of these connectors means that multiple vendors and options are available in the market to support integration and avoids a sole-source situation with a single supplier.

4.2. Rugged Connectors:

Metalized board level transceivers, such as LCs, and ruggedized MTPs are recent advances that improve fiber performance in military ground vehicles. Using commercial form factors but using more robust materials lets integrators keep existing opto electronic transceiver profiles while gaining longer lifecycle and more durable interconnects without degrading optical pathways (see Figure 3).

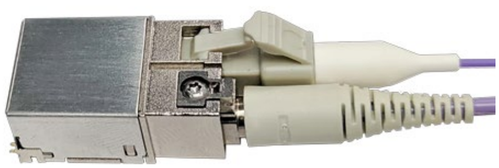

Figure 3 Comparison of Telecom and Rugged LC

Metalized LCs are single channel examples: replacing plastic bodies with all metal designs fixes many of the shortcomings of commercial datacom parts, improving performance over temperature, shock, and vibration and reducing deformation and misalignment under continuous load. These materials were also chosen for chemical resistance because vehicle environments expose connectors to water, salt fog, mud, snow, sand, and harsher contaminants (bleach, hydraulic fluid, refrigerants).

Figure 4 Rugged Parallel Transceiver

Multichannel/parallel connectors have followed the same trend. Commercial multichannel designs (e.g., USConec variants) are being adapted for vehicles, but shock, vibration, and elevated temperature requirements are pushing commercial materials to their limits. With datacom components typically rated to 85°C, the military market needs solutions rated for sustained 125°C, 150°C, 200°C and above; several groups have been developing high temperature, rugged multi channel termini over the past 5+ years to meet those needs (see Figure 4).

4.3. Ruggedized Cable Harnesses:

Fiber optic cable harnesses have always been available in a variety of shapes and sizes, but the demands of a rugged optical network require more robust construction and durable materials. Over the years, significant effort has gone into strengthening and protecting the glass fibers used in these networks to withstand an increasing range of operating environments. Cable construction varies by application to meet environmental needs. At the glass layer, traditional fiber coatings are often replaced with tougher materials to withstand higher temperatures and to reduce long-term degradation in continuous-bend installations. Chemical restrictions also govern cable material selection, and the inclusion of fire-suppressant compounds is frequently incorporated into cables intended for vehicle use to protect occupants in catastrophic events. Rugged fiber cables commonly include multiple protective layers beyond what a standard datacom cable would use to boost mechanical durability.

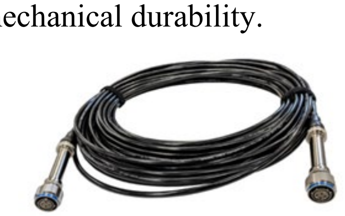

Figure 5 Rugged Optical Harness

Strength members, traditionally nylon threads, are commonly replaced with heavier-duty aramid fibers for greater tensile strength. PEEK or similar polymers are used as buffers to provide crush resistance for the glass. Metallic armor wraps add both crush protection and resistance to snags and cuts. Materials such as PTFE are selected for flexibility and wear resistance in high-vibration environments subject to constant flexing fatigue, and outer jackets are formulated to resist abrasive wear over long service life.

Figure 6 Variety of Ruggedized Fiber Cables

These design principles apply not only to single-fiber runs; as bandwidth demand grows, multifiber solutions have entered the market. Multifiber cables follow the same construction approaches as single-fiber variants and have proven effective in applications that require commercial-grade data performance. The industry has codified minimum performance requirements: organizations such as ARINC have produced standards (i.e., ARINC 802) defining fiber-optic cable requirements for aerospace. The MIL-PRF-84045 military specification addresses cable use in military applications. Both types of standards include classifications for single-fiber and multifiber solutions, giving designers flexibility and helping ensure application requirements are not constrained by a single specification.

Figure 7 Rugged Field Splice Kit

On rare occasions when a fiber is damaged, there have been significant improvements in rugged field splice design. An on-site repair can be accomplished in less than 30 minutes when using a field-deployable kit that includes the equipment and materials to perform the splice. The resulting splice has a pull-force rating equivalent to OEM cable construction.

4.4. Fiber Optic Rotary Joints:

Fiber-optic rotary joints transfer optical signals across rotating interfaces (turrets, masts, gimbals) in single-, dual-, or multi-channel configurations; higher counts are usually implemented by stacking modules or using a common de-rotating optical element. Rugged vehicle designs prioritize robust housings, environmental sealing, precision bearings/alignment and shock isolation so optical alignment and insertion loss stay within spec under vibration, thermal cycling, contamination and impact. Notably, vehicle-grade FORJs have been validated against gunfire-shock profiles, with pre/post optical checks to confirm survivability. Singlemode FORJs demand tighter mechanical tolerances than multimode, and internal optics (lenses, WDM/multiplexing elements) are typically the most vulnerable components, so ruggedization focuses on protecting and stabilizing those elements.

4.5. Rugged media Converters:

Rugged electro-optical media converters support Fast Ethernet, Gigabit Ethernet, 10 Gigabit Ethernet, and even 100 Gigabit

Ethernet with a hardened mechanical and EMI-protected chassis to deliver reliable multimode-fiber links in severely harsh vehicle environments. Combined MIL-DTL-38999 sealing, shock/vibration qualification, and corrosion-resistant materials address the primary environmental threats on ground platforms (mechanical shock from terrain and blast, continuous vibration, ingress of dust/water, salt atmosphere, and extreme thermal cycles). 28 VDC input power is standard for vehicle power systems. EMI/RFI hardening (plating and chassis) helps maintain link integrity in electronically dense vehicle environments where radios, radar, and other RF emitters are present. Mechanical and electrical pinouts conform to MIL-DTL-38999 wiring practices for robust interconnect to vehicle harnesses. Optical fiber reduces weight, eliminates ground-loop and common-mode noise coupling compared with copper, and extends backbone distances inside and between vehicle modules — all important in modern vehicle networks.

4.6. Connector Integrated Transceiver

MIL-DTL-38999 connector-based optical transceivers are capable of delivering high-speed multimode-fiber links (up to 10.3125 Gbps) in aggressively harsh environments. Engineered as integrated bulkhead transceivers (MIL-DTL-38999 Series III), these products couple high data-rate optical performance with military-grade environmental protection and EMI hardening to ensure reliable, mission-critical communications in the field. Sealed MIL-DTL-38999 Series III optical interfaces are water-tight to MIL-STD-810 / IP67 / NEMA-4X when mated and have a wide operating temperature range of –40°C to +85°C.

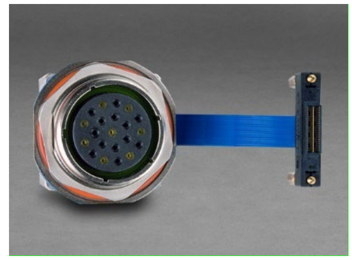

Figure 8 Connector Integrated Transceiver

This combination of mechanical sealing, military-grade materials, and verified environmental/EMC qualifications makes MIL-DTL-38999 connector-based optical transceivers ideal for deployed communications on ground vehicles, where reliability under shock, vibration, moisture, salt atmosphere, and extreme temperatures is mandatory.

4.7. Rugged Active Optical Cable

MIL-DTL-38999 connector-based active optical cables can support high-speed applications (up to 25 Gbps) in aggressively harsh environments. Rugged active optical cables provide crush resistance, impact resistance, and cyclic-flexing endurance for repeated mating, vehicle installation strain, and handling. These cables support operating temperatures from –40°C to +85°C and are qualified for the shock and vibration levels typical of off-road and combat vehicle dynamics. The combination of MIL-type connectorization, proven mechanical test criteria, rugged cable construction, and temperature/shock/vibration qualifications makes a rugged active optical cable well suited for vehicle harness runs, external access panels, and onboard I/O where repeated mating, shock, vibration, moisture, abrasion, and rodent exposure are routine. The metal shell and grounded center slug support robust EMI/grounding practices that are critical inside vehicle electronic bays.

4.8. Architecture Options:

With the variety of applications requiring fiber-optic solutions, network architects need more than ruggedized components to build an appropriate optical network. Designers can employ several topologies and transmission methods to meet mission needs.

Traditional point-to-point architectures are readily implemented with a single fiber or duplex-fiber configuration. Often called discrete optical channels, this approach has the longest history of use in military aerospace, naval, and ground applications. However, as bandwidth demands grow, designers must provide scalable paths for capacity expansion.

One straightforward option is parallel opto-electronic transceivers: devices that include multiple transmit and receive circuits and carry multiple signals side-by-side over separate glass fibers collected into a multifiber cable. Parallel transceivers and multifiber assemblies increase bandwidth simply by adding lanes (additional fiber pairs). This approach is particularly well suited for short-reach links, since multimode parallel modules have a long service pedigree and broad market availability.

When longer reach is required, or additional fiber lanes cannot be installed, wavelength division multiplexing (WDM) is an effective alternative. WDM combines multiple wavelengths onto a single fiber so each wavelength independently carries an optical channel. WDM supports long-term expansion by allowing extra wavelengths to be added without installing additional fibers. It is especially useful where extra fiber runs are impractical — for example, legacy installations or assemblies with a central rotary joint — because physical bandwidth is no longer limited by the number of fibers.

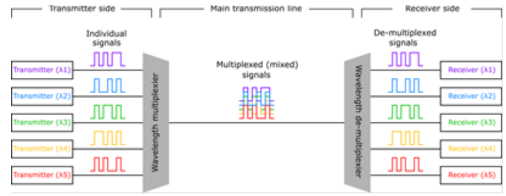

Figure 9 WDM Architecture [5]

WDM has been used in aerospace for over 20 years (bi-directional two-wavelength links are common) to reduce the cable plant. Recently, WDM adoption has increased in naval and ground systems. One field example is a ground radar that was deployed with 16 wavelengths multiplexed onto a single fiber passing through an existing rotary joint; this allowed the network to reach 80 Gbps without changing the slip ring. The system is planned to expand to 160 Gbps by adding 16 additional wavelengths, which would double capacity on the existing fiber and avoid costly mechanical changes to the rotary joint.

5. FUTURE WORK

Looking ahead, there are a few important areas to focus on to further advance fiber optic use in ground combat vehicles. One key topic is radiation tolerance. While radiation can cause fiber darkening—an increase in optical attenuation—this really isn’t a major concern for ground vehicles because the cable lengths are relatively short compared to space or sub-sea applications. However, more attention needs to be paid to radiation’s effects on optical components like the lenses in Fiber Optic Rotary Joints and Wavelength Division Multiplexing (WDM) elements. These parts can suffer radiation-induced losses that impact overall system performance, so targeted testing and mitigation strategies around these components are necessary.

At the system level, designing built-in test (BIT) capabilities is crucial. By integrating BIT into the architecture, the network can continuously self-validate its performance and quickly isolate faults when they occur. This makes maintenance and repairs more efficient and improves mission readiness. A well-designed BIT framework also supports MOSA goals by enabling modular, interoperable components that communicate their status clearly, simplifying integration and sustainment across vehicle platforms.

Finally, future work should include comprehensive, full-harness environmental testing that mimics real vehicle stresses, and continued refinement of architecture trade-offs; balancing modularity, robustness, maintainability, and performance to meet evolving mission needs.

6. CONCLUSIONS

Advances in rugged fiber optic technology and system-level integration have made fiber a reliable and high-performance backbone for ground combat vehicle networks. Through hardened cable constructions, military-grade connectors, and proven environmental qualifications, fiber optics can withstand the unique mechanical, thermal, and contamination challenges found in vehicle environments. Furthermore, scalable architecture options like parallel transceivers and wavelength division multiplexing provide flexible paths to meet growing bandwidth demands without costly infrastructure changes. Continued focus on maintainability, diagnostics, and standards-based ruggedization will accelerate fiber adoption, unlocking crucial bandwidth for future mission success.

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9. ACRONYMS

GVSC	Ground Vehicle System Center
WDM	Wavelength Division Multiplexing
FOD	Foreign Object Debris
PEEK	Polyetheretherketone
BIT	Built In Test