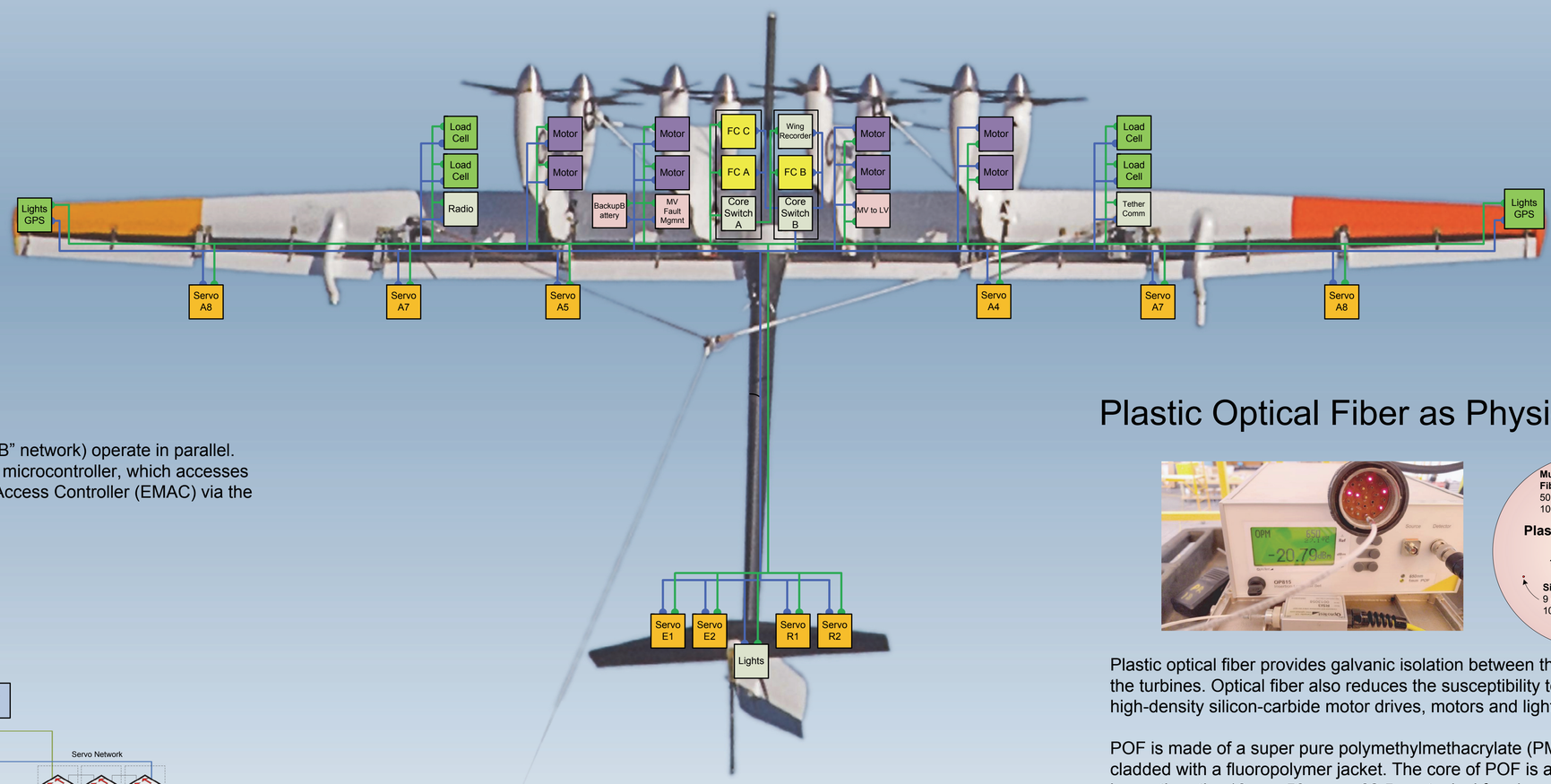
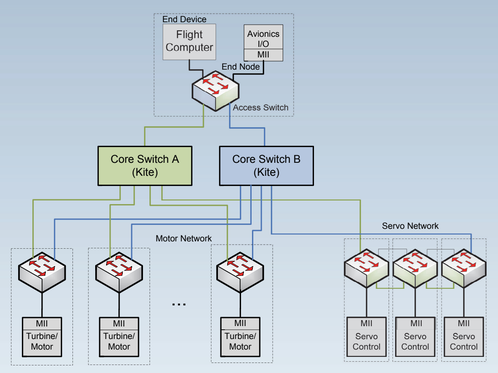
A Low-Cost Fiber Optic Avionics Network for Control of an Energy Kite

Kurt Hallamasek, Eric Chin, Paul Miller, Mike Mu, Michael Scarito, Eric Uhrhane



Network Topology

Dual-redundant networks (an “A” network and a “B” network) operate in parallel. Every end system on the kite includes a TMS570 microcontroller, which accesses both networks through its single Ethernet Media Access Controller (EMAC) via the Access Switch. All links are full-duplex.

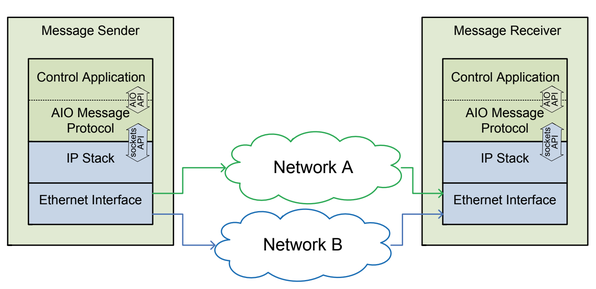


A primary function of the Access Switch is to prohibit traffic between ports that connect to the A networks and ports that connect to the B networks. To this end, network facing ports are isolated from each other using port-based VLANs (Virtual Local Area Networks).

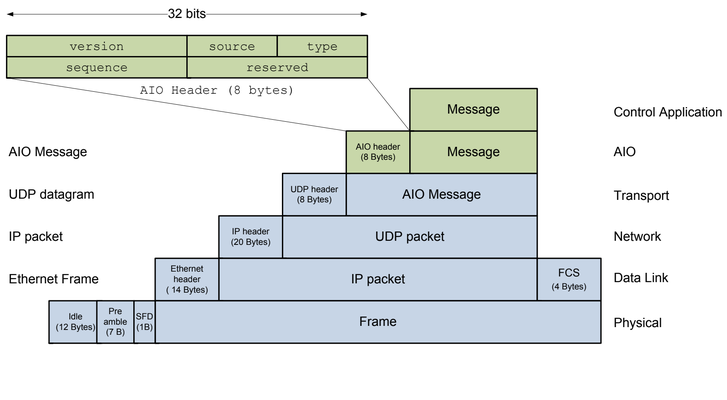
The kite network supports daisy chain topologies, in addition to star topologies. The turbine motors, which exchange data at a kilohertz rate, connect directly to the core switch for low-latency connections. The connections to control surface servos are daisy-chained to reduce cabling and core switch port count.

Network Protocol

The network protocol is comprised of the AIO protocol layer, a thin layer in user space, built on top of the unmodified UDP/IP protocol stack. Rather than relying on TCP on the kite network, the AIO message protocol manages data availability, in a manner suitable for real-time control. The User Datagram Protocol (UDP) allows for multicast addressing, allowing datagrams from one sender to reach multiple destinations. When a motor controllers shares state information with the other seven motors, the controller sends a status message *once* to the multicast group which has all motor controllers as members. The Access Switch on the originating motor controller duplicates the message as it forwards it to each of the Core Switches. In the Core Switches, messages are replicated and forwarded based on statically programmed multicast routes to only the ports associated with the members of the multicast group (excluding the ingress port).



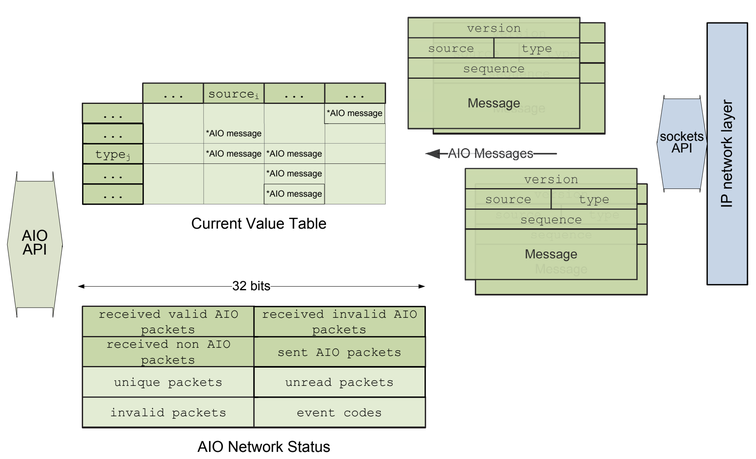
Each message is received in duplicate at each of the destination nodes. Message deduplication at the destination node is handled in the Avionics I/O (AIO) protocol layer. This layer also provides services for diagnostic monitoring.



Redundancy Management

The Current Value Table (CVT) is the interface for the Control Application to access data received via the kite network. For each message type, the CVT points to the most recent message received from each sender, based on the sequence number in the AIO header. An acceptance window for the 16-bit sequence number defines how many sequence numbers ahead of the entry to consider more recent (5K). An expiration time defines the maximum amount of time to consider the current message within the CVT as current (0.5 sec). When an entry becomes stale, all messages are accepted.

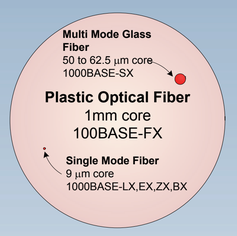
Note that there is no requirement for a global clock to manage messaging on the network.



Data Integrity

Message integrity is assured by the error detection features built into the IP stack. Corruptions, detected on any layer, simply result in discarding the frame or packet. The Physical Layer discards runt frames. The Link Layer uses the Frame Check Sequence (FCS), a 32 bit cyclic redundancy check (CRC) to check data integrity. Per the 802.3 standard, undetected byte errors are allowed to occur at a rate of 5×10 -14 per byte of data. In the IP layer, the frame has to pass IP parity checks.
In the Transport Layer, with UDP protocol, checksum calculation is optional in IPv4.
In the AIO layer, the version number must be correct and the message type must be recognized for the message to be entered into the CVT.

Plastic Optical Fiber as Physical Medium



Plastic optical fiber provides galvanic isolation between the Flight Control Units and the turbines. Optical fiber also reduces the susceptibility to EMI, in particular from high-density silicon-carbide motor drives, motors and lightning.

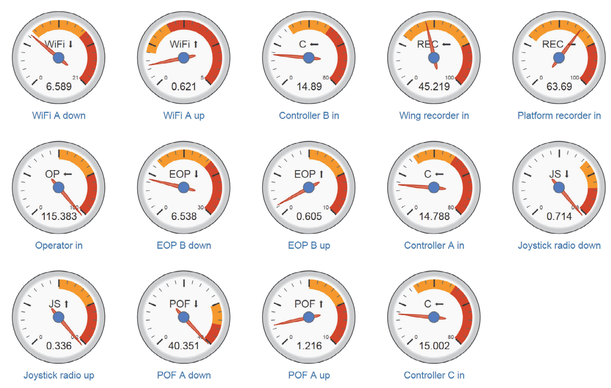
POF is made of a super pure polymethylmethacrylate (PMMA) fiber core, which is cladded with a fluoropolymer jacket. The core of POF is about 1mm - considerably larger than the 10 µm, 50 µm or 62.5 µm typical for glass optical fiber (GOF). The comparatively large diameter core of the POF reduces the mechanical precision required by connectors and allows the use low-cost high-density connector systems suitable for airborne environments. The numerical aperture is also large, allowing the use of low-cost LED sources as transmitters. POF is also easy and economical to terminate for development and in the field.

Network Configuration

The kite network is automatically configured by the software by means of a configuration file. This human-readable (.yaml) configuration file defines the network topology and the connections for the nodes that exist on the network. It defines the message type senders, the rates at which messages are sent, and recipients. This configuration computes the message routes at each access switch or core switch, where message routes are statically programmed.

Bandwidth Control

By design, nodes on the network transmit messages at a constant rate. This can be expected in a real-time feedback control system: sensors are read and control actions are computed at fixed rates. When the kite is operational, there are no event-driven messages on the kite network.



The network configuration file also allocates bandwidth. The network switches can be automatically configured to block unknown traffic and to handle non-operational (debugging or provisioning) traffic at a lower priority. The network switches provide port-level ingress control to guard against packet storms and to allow traffic shaping. This port throttling mechanism is used on the kite network to guard against babbling idiot failures.

Failure Mode	AIO Mitigation
Loss of Power	Dual independent power system
Loss of Communication	Dual redundant networks
Invalid Messages	Invalid messages discarded at each layer in the protocol stack: • AIO Layer: Invalid 16-bit AIO version number • Transport layer: Optional 16-bit one's complement checksum • IP Packet: 16-bit one's complement checksum • Ethernet Frame: 32-bit Ethernet CRC (FCS) Invalid Ethernet frame formats • Physical Layer: Specified timing of bitstream, interframe gap Runt frames are discarded
Non-Responsive Node	Message sent at constant rates, as defined in the network configuration file. Message rates tallied by CVT used to detect non-responsive nodes in the control application. Functional redundancy allows kite to operate with at least one failed node. Each node can restart to clear transient faults.
Babbling Idiot	Port throttling keeps any one node from consuming all network bandwidth.

AIO Network Failure Mode Mitigation

Criterion	Performance
Operating Speed	100 Mbit/sec
Network Capacity	50 Mbit/sec/link
Data Latency	< 200 µs on LAN, 10 ms on IP radio links typical
Maximum Bus Length	Max link length 50 m
Load Analysis	Automated profiling of network utilization
Network Expansion	Star and daisy-chain topologies
Common Cause/Mode Failure Containment	Independent networks with redundant power supplies
Availability	Zero failover time
Redundancy Management	Current Value Table in AIO protocol layer
Message Scheduling	Network Configuration File sets network topology, rate and route of messages
Electromagnetic Compatibility	Plastic Optical Fiber as physical medium is immune to HIRF and lightning. Does not emit EMI.
Continued Airworthiness	Continuous monitoring of correct connectivity. Continuous monitoring of link statistics on each port. Continuous monitoring of received optical signal power on each port.

AIO Network Performance

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