# Optical Control Network for Avionics Applications Using a WDM Packet Ring

Rui Wang, *Student Member, IEEE,* Richard J. Black, *Senior Member, IEEE,* Behzad Moslehi, *Senior Member, IEEE,* Alireza R. Behbahani, and Biswananth Mukherjee, *Fellow, IEEE*

***Abstract*—We propose *AViAtion real-Time Adaptive Ring* (AVATAR) as a potential solution for the integrated communication infrastructure for future aero-engine control systems. AVATAR features an Ethernet-over-WDM architecture. It employs Reconfigurable Optical Add/Drop Multiplexer (ROADM) as node technology. Compared to existing serialized data bus, e.g., Time-Triggered Protocol (TTP), AVATAR exploits multi-wavelength and spatial reuse properties of an optical WDM ring through sophisticated packet scheduling. To quantitatively evaluate the advantages over existing avionic networks, and to understand the architectural parameters of AVATAR, optimal scheduling methods using Mixed Integer Linear Programming, as well as a simple, near-optimal heuristic are presented. Numerical results demonstrate the superiority of AVATAR, with a simple two-channel configuration more than doubling the capacity of TTP.**

***Index Terms*—Aero-engine control network, Ethernet-over-WDM, ROADM, real-time, avionics, scheduling, heuristic.**

## I. Introduction

THERE is considerable interest in exploring options to deliver affordable, distributed, high-temperature-resistant intelligent engine controls for gas turbine and aerospace vehicle applications. The control architecture has to be robust and scalable, provide lower life cycle cost, mitigate obsolescence, reduce weight, support advanced control algorithms, and create an “eco-system” that sustains future engine control infrastructure. There are currently three options available: (1) lightweight fiber optics, (2) wireless, and (3) distributed control using databus. In this research, we are exploring fiber optics in a distributed configuration.

Full Authority Digital Engine Control (FADEC) has evolved over three decades and become the norm for aero-engine control today. However, it is faced with major challenges stated above. For instance, due to its centralized architecture, every control element is connected with a dedicated copper wire. This organization results in bulky wirings, especially when newer functionalities are added, and significantly greater complexity and weight are incurred. Stressing these emerging issues, the aero-propulsion community is undergoing a paradigm shift to a more distributed and open system design [1]. A distributed control architecture facilitates development of non-proprietary control modules and draws out a sustainable evolution path for replacement of obsolete components. This next-generation control system should employ a networking infrastructure that lends itself well to desired features such as light weight, high capacity, high reliability, modularity, scalability, etc.

Optical Wavelength-Division Multiplexing (WDM) is a promising technology to not only alleviate the emerging wiring nightmare but to eradicate communication infrastructure obsolescence due to capacity exhaustion or control architecture redesign [2]–[8]. The WDM platform can support a mix of on-board signal rates and protocols originating from a large set of data sources, connected by optical fiber, including both analog and digital [6]. The economic benefits of WDM are two-fold. First, WDM provides the ability to significantly scale fiber capacity by multiplexing many optical channels along a single fiber. Second, WDM enables a significant reduction in the number, and cost, of Optical-Electrical-Optical (OEO) translations used in the previous fiber optic technologies in repeaters. Compared to copper, a fiber-based plant will significantly lower the wiring complexity and weight. Also, fiber optics may offer much higher operating temperature. It was demonstrated in [9] the proof-of-concept for fiber optics based gas sensing in a harsh environment.

We propose using a WDM ring to interconnect control elements (controllers, sensors, actuators, etc), and support real-time communications [2], [3]. The rationale of the choice includes structural simplicity and scalability, self-healing, inherent support for distributed applications, etc. A good body of research exists for the cost-efficient design of such networks. Reference [10] seeks to minimize Synchronous Optical Networking (SONET) Add-Drop Multiplexors (ADMs) usage at wavelength granularity assignment. The scheduling of a uniform capacity, full-mesh overlay on WDM ring is considered in [11]. References [12]–[16] studied the design problem with *traffic grooming*, which is a mechanism to pack connections of different bandwidth granularities onto channels with full wavelength capacity. In particular, [16] [17] consider the network setting where a single node is capable of electronic switching and hence serves as a “hub”. For more detailed review on grooming in WDM ring networks, please refer to [18], [19].

Most of the previous work focused on scheduling of physical network resources for circuit services. Some work on packet scheduling in a WDM ring considered only slotted time and uniform packet lengths (and thereby greatly simplified the problem along the time dimension). Our work jointly considers scheduling of physical resources in the *time domain*

R. Wang and B. Mukherjee are with the University of California, Davis, CA 95616, e-mail: (ruiwang@ucdavis.edu; bmukherjee@ucdavis.edu).

R. J. Black and B. Moslehi are with Intelligent Fiber Optic Systems Corp. (IFOS), 2363 Calle Del Mundo, Santa Clara, CA 95054.

A. R. Behbahani is with Air Force Research Laboratory, Wright-Patterson AFB, OH 45433.

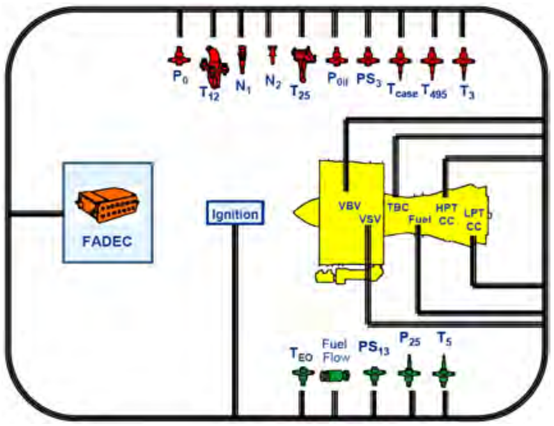



Fig. 1. Aero-engine control with shared communication infrastructure [1].

for real-time, variable-length packets in a WDM ring, given the network configuration.

Researchers have also studied scheduling problems in a sensor network context. For instance, a foundational study on *divisable* load scheduling is presented for linear networks in [20]. It jointly considers the scheduling of computation and communication resources, and gives the analytically-tractable, closed-form solution of optimal schedule. Some later studies advanced the theory by considering time-varying computation and communication speed, as well as with stochastic workloads [21], [22]. In contrast, our study looks at scheduling of *non-divisable* packets over a full-fledged optical communication infrastructure that interconnects avionic sensors. The problem, due to its different set of assumptions and network settings, is analytically intractable and thus leads to a different solution technique.

This study has merits in following three aspects. (1) *Traffic engineering*: given a network configuration, we would like to load-balance the known a *priori* real-time traffic over different wavelength channels. (2) *Network engineering*: to accommodate new engine functionalities coupled with increasing traffic volume, we need to re-distribute the load in the network, with minimum upgrade to the network. (3) *Network design*: the optimal schedules that we obtain under different network configurations can be used to guide the choice of design parameters.

The rest of the study is organized as follows. Section II details AVATAR architecture in light of traditional data bus network. The scheduling problem in AVATAR is formulated as an MILP in Section III. A fast and near-optimal heuristic is presented in Section IV. Numerical results of optimal scheduling and heuristic are shown in Section V. Section VI concludes the study.

## II. Network Architecture

### A. Distributed Aero-Engine Control

A typical control system consists of a controller, sensors, and actuators, together forming a closed loop. In a centralized FADEC architecture, all control loop closures are done at the designated site hosting FADEC. Distributed control is a mechanism for the proper implementation of systems engineering processes in aero-propulsion engine systems. The distributed control architecture is inherently more powerful, flexible, and scalable than a centralized control approach. In the long term, businesses can achieve greater efficiencies and expect higher rates of return on investment by implementing this technology.

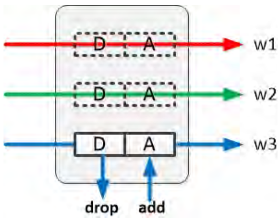
The potential benefits of a "distributed architecture" can be accrued only if the building blocks of this architecture are truly modular and generic, so that they can be used in multiple applications without any changes. Contrary to aggregating control computations at one node, such architecture distributes the control law processing burdens throughout the network, at various "smart nodes".

The successful realization of such a distributed smart-node-based control system would provide significant modularity and scalability benefits to the distributed platform, and permit an affordable expansion of an existing FADEC or flight control system, or the assembly of a new system with these generic reusable smart nodes, as shown in Fig. 1. Furthermore, the distributed architecture would greatly reduce the system-wide impact of each and every obsolescence issue, or new technology-driven update cycles. Another significant consequence of this "distribution" of I/O among the smart nodes would be the reduction of the "heat load" on the remaining "central" FADEC, which in turn would increase its reliability, and enable the development of the next generation of smaller FADECs, with reduced thermal load and greater opportunity for throughput capacity expansion. In this work, we develop for distributed control a new communication architecture using fiber optics with a WDM platform to communicate with the sensors/actuators and smart component nodes.

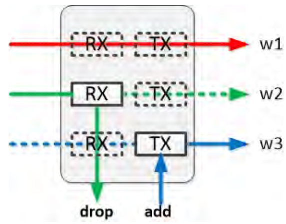
### B. Existing Network Architecture

*1) Time-Triggered Protocol (TTP):* One relatively-mature and widely-deployed architecture to support real-time avionic applications is the *Time-Triggered Architecture* (TTA), the original design and development of which date decades back. A fault-tolerant global time base is critical in time-triggered operations. It is used to specify the interfaces among the nodes, to simplify the communication and agreement protocols, to perform prompt error detection, and to guarantee the timeliness of real-time applications [23]. There are two classes of Time-Triggered Protocol (TTP), TTP/A and TTP/C, both of which use Time Division Multiple Access (TDMA) scheme for collision-free channel allocation. Messages, once injected into the channel, are broadcast to all end hosts. Thus, TTP is a *deterministic* communication protocol. TTP/C is now in industrial use in the aerospace sector, e.g., a number of on-board control systems in Airbus A380 and Boeing 787 aircraft are communicating by TTP [24].

*2) Time-Triggered Ethernet (TTE):* Later efforts aimed at provisioning real-time and non-real-time services over one single, coherent communication architecture, Time-Triggered Ethernet (TTE) [24], [25]. The TTE framing complies with standardized raw Ethernet messages. It distinguishes *time-triggered* (TT) messages from *event-triggered* (ET) messages by the *Type Field*. ET messages receive *best-effort* service, a standard service provisioned by traditional Ethernet. By contrast, TT messages are characterized by temporal determinism




(a)




(b)

Fig. 2. (a) A/D model, A: add, D: drop; (b) CDC model, TX: transmitter, RX: receiver.

and strict priority over ET messages. The two message classes are identical in frame structure and addressing conventions. The only difference is in the control imposed by a TTE switch. The TT messages are forwarded at scheduled slots, and preempt, if any, ongoing ET message transmissions. Regular ET messages, together with preempted ones, use Carrier Sense Multiple Access with Collision Detection (CSMA/CD). Thus, ET messages receive *non-deterministic* services.

*3) Aeronautical Radio, Incorporated (ARINC) 825:* ARINC 825 specifies Controller Area Network (CAN) connectors and wiring considerations, and is a form of a communication bus network [26], which has been identified by airframers as an important baseline network for aircrafts. It is also based on CSMA/CD [27], and thus is non-deterministic. ARINC 825 adopts a similar access control scheme as TTE, namely, higher priority messages preempt the transmission of lower priority messages. In this way, CD is arbitrated by message priority. Higher priority traffic thus receives time-triggered, scheduled services as in TTP. ARINC 825 is considered by some to be an ideal data bus, since it offers many advantages such as low implementation cost, maximum interoperability, configuration flexibility, good error detection, and optimal bandwidth. The ARINC 825 standard was driven by Boeing and Airbus and defines communication standard for airborne systems using CAN. Data rates supported by ARINC 825 data bus are: 1000 kbit/s, 500 kbit/s, 250 kbit/s, 125 kbit/s, and 83.333 kbit/s.

### C. WDM-Based AVATAR Architecture

We propose *AViAtion real-Time Adaptive Ring* (AVATAR) to be a potential solution for the integrated communication infrastructure for a future aero-engine control system. AVATAR employs an Ethernet-over-WDM architecture. It is constructed by Reconfigurable Optical Add/Drop Multiplexers (ROADMs) interconnected via multi-wavelength fibers. We consider two ROADM architectures in this study, the traditional Add/Drop pair (A/D) model and the newer *Colorless, Directionless, Contentionless* (CDC) model, abstractions of which are shown in Figs. 2a and 2b, respectively. Each ROADM is equipped with a number of tunable transceivers (add/drop pairs). In the A/D model, the transmitter (add) and receiver (drop) of the same transceiver are tuned together in a pair-wise fashion, in other words, coupled. The CDC model, on the other hand, decouples the transmitter and receiver, such that they can be tuned independently to different wavelengths, see Fig. 2b. Thus, CDC model is more flexible. Dashed boxes indicate the positions transceiver pairs can tune to, while solid boxes indicate the positions the transceivers are actually parked on. For example, in Fig. 2a, the add/drop pair is parked on $w_3$, and hence the incoming traffic is dropped from $w_3$, and outgoing traffic is added onto $w_3$. In Fig. 2b, the transmitter and receiver can be tuned to different wavelengths, viz., the receiver is parked on $w_2$ while the transmitter on $w_3$. Under this configuration, incoming traffic is dropped from $w_2$ while outgoing traffic is added onto $w_3$. Express wavelengths are those that bypass a node, e.g., $w_1$, $w_2$ in Fig. 2a and $w_1$ in Fig. 2b. In this study, we assume an ideal tuning model, that is, transitioning from any configuration of the transceivers and express wavelengths to another can be done with negligible tuning delay. Although packet-level fast tunable lasers are not yet commercially available, this ideal tuning model focuses our study on balanced resource investments (wavelengths and transceivers), and design of intelligent scheduling schemes.

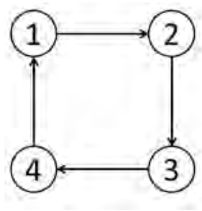
| Symbol | datum | source ID | destination ID | forward error correction | total message |
|---|---|---|---|---|---|
| | bits | bits | bits | bits | bits |
| $P_0$ | 36 | 16 | 16 | 7 | 75 |
| $T_{12}$ | 36 | 16 | 16 | 7 | 75 |
| $N_1$ | 36 | 16 | 16 | 7 | 75 |
| $N_2$ | 36 | 16 | 16 | 7 | 75 |
| $T_{25}$ | 36 | 16 | 16 | 7 | 75 |
| $P_{oil}$ | 36 | 16 | 16 | 7 | 75 |
| $PS_3$ | 36 | 16 | 16 | 7 | 75 |
| $T_{case}$ | 36 | 16 | 16 | 7 | 75 |
| $T_{495}$ | 36 | 16 | 16 | 7 | 75 |
| $T_3$ | 36 | 16 | 16 | 7 | 75 |
| $T_{E0}$ | 36 | 16 | 16 | 7 | 75 |
| Fuel Flow | 36 | 16 | 16 | 7 | 75 |
| $PS_{13}$ | 36 | 16 | 16 | 7 | 75 |
| $P_{25}$ | 36 | 16 | 16 | 7 | 75 |
| $T_5$ | 36 | 16 | 16 | 7 | 75 |
| VBV | 36 | 16 | 16 | 7 | 75 |
| VSV | 36 | 16 | 16 | 7 | 75 |
| TBC | 36 | 16 | 16 | 7 | 75 |
| Fuel | 36 | 16 | 16 | 7 | 75 |
| HPTCC | 36 | 16 | 16 | 7 | 75 |
| LPTCC | 36 | 16 | 16 | 7 | 75 |
| Ignition | 36 | 16 | 16 | 7 | 75 |
| Thrust Reverser | 36 | 16 | 16 | 7 | 75 |
| Solenoids | 36 | 16 | 16 | 7 | 75 |
| Total bits per cycle | | | | | 1800 |
| Max. effective bit rate 20 Hz ( 50 msec interval) | | | | | 36000 |
| Max. effective bit rate 100 Hz ( 10 msec interal) | | | | | 180000 |

Fig. 3. Estimated traffic volume of the distributed aero-engine controller in Fig. 1 [1].

In contrast to the single-channel broadcasting method in TTP, AVATAR exploits multi-channel access and spatial reuse in a WDM ring. Over the segment between a source and a sink, we schedule a wavelength and a continuous time interval to transmit sensor/actuator messages packaged in Ethernet frames. By carefully assigning a wavelength and a time interval to each Ethernet frame, we can achieve both real-time requirement (dictated by bounded delays) and efficient channel utilization.

## III. Problem Statement

In a fully-distributed aero-engine control system, control law processing and loop closure are expected to be performed at various nodes in the network instead of at one designated node as in FADEC architecture. Therefore, we assume a general traffic model that allows communication between any node pairs. As mentioned earlier, network traffic is expected




| Data flow | Source ID | Sink ID | Total message (kbits) |
|---|---|---|---|
| $r_1$ | 4 | 3 | 3 |
| $r_2$ | 3 | 1 | 2 |
| $r_3$ | 3 | 2 | 1 |
| $r_4$ | 1 | 4 | 5 |

Fig. 4. Four-node ring with four packets to schedule.

to be Ethernet frames (also called packets in this paper), packaging data from/to sensors/actuators. In a closed-loop engine control system, it is safe to assume that traffic exhibits *determinism*, that is, the time evolution of the traffic can be predicted. As shown in Fig. 3, network traffic is *periodic* and specified by *source*, *destination*, and *total message bits*, that is, the amount of data (measured in bits) generated per *update interval*. In real-time control, it is required that all analog channels are sampled simultaneously to avoid phase lag during the digitization process, implications of which are estimated by assuming that delivery of messages from all control elements (even those used at lower update rates) occurs within the span of the fastest update interval of the system [1]. For each message, we need to assign a continuous wavelength, a transmitter at source, a receiver at destination, and a continuous time interval in which those resources are available to carry out the transmission.

In TTP architecture, when the aggregated traffic volume increases, e.g., new control elements (nodes) are added, it is inevitable that all the nodes need to upgrade their operating line rate. In AVATAR, however, leveraging the flexibility of ROADM, we can progressively deploy more transceivers and light up new wavelengths as needed, without replacing the Ethernet card at each node with higher line rates. Thus, the scheduling intelligence is to most efficiently pack those messages onto wavelength channels in a “load-balanced” way, such that the multi-channel advantages are properly exploited. We adopt *finish time*, the length of the payload, as the performance metric.

### A. Illustrative Examples

We show using the example in Fig. 4 the impacts of different resource configuration and scheduling on the finish time. Consider a four-node WDM ring. A traffic request is specified by source node ID, destination node ID, and kbits/update (total message bits). Let the update rate be 100 Hz [1].

We first schedule the packets sequentially and get a trivial solution that gives the upper bound of the finish time, as in Fig. 5a. In this case, required line-rate≥11 kbits×100 Hz=1.1 Mbits/sec while wavelength 2 sits idle. All transceivers are parked on $w_1$ throughout the entire update interval (a frame). This naive serialized scheduling is effectively TTP.

Schedule 2, Fig. 5b, is optimal under this resource configuration, namely, 2 wavelengths and 1 transceiver at each node. Note that we parallelized messages $r_3$ and $r_4$ to reduce the finish time. In this case, required line-rate≥10 kbits×100 Hz=1 Mbits/sec, and transceivers at nodes 1 and 4 need be

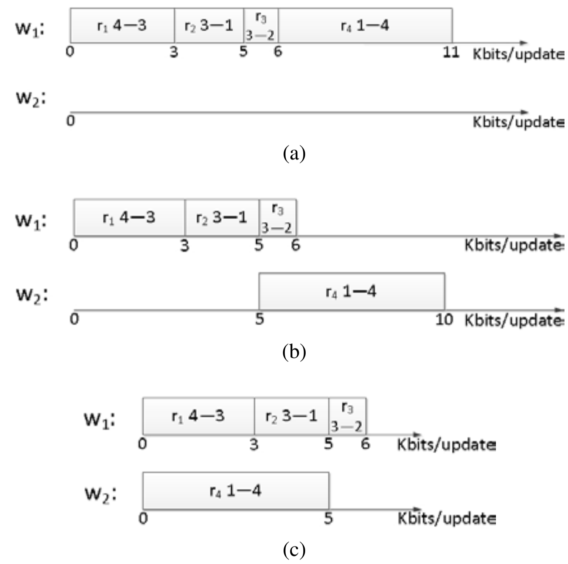



Fig. 5. Frame schedule with different sophistication and resource configuration. (a) Serialized schedule (TTP). (b) Two wavelengths, 1 transceiver at each node. (c) Same as (b) with 1 additional transceiver at nodes 1 and 4.

tuned to wavelength 2 at time 5 for the transmission of $r_4$. Note also that the transceivers are the limiting resources that cause the under-utilization of wavelength resources.

In Schedule 3, Fig. 5c, we try to better utilize the wavelength resources by introducing one more transceiver at node 1 and at node 4, so that we can parallelize more packet transmissions and further reduce the finish time. Note that an additional transceiver eliminates the contentions between $r_4$ and $r_1$, $r_2$ respectively at nodes 4 and 1, and thereby increases the utilization of wavelength resources. In this case, required line-rate≥6 kbits×100 Hz=0.6 Mbits/sec, so we can assign the additional transceiver at nodes 1 and 4 to $r_4$, and no transceiver reconfiguration is needed.

Thus, by careful scheduling and balanced resource configuration, we can reduce the line rate from 1.1 Mbits/s→ 1 Mbits/s→ 0.6 Mbits/s in this example. We develop below a Mixed Integer Linear Program (MILP) to obtain optimal schedules for general resource configurations and traffic.

### B. Problem Formulation

*Given:*

- $K$: number of packets.
- $N$: number of nodes.
- $W$: number of wavelengths.
- $P_i$: number of transceivers at each node.
- $(s_k, d_k)$: source/destination pair of $k$th packet, hereafter referred to as $k$.
- $h_k$: packet length of $k$.

*Binary variables:*

- $\lambda_w^k$: 1 iff wavelength $w$ is assigned to $k$.
- $t_{wp}^k$: 1 iff the transmitter of transceiver $p$ at node $s_k$ is assigned to $k$ and operates on wavelength $w$.
- $r_{wp}^k$: 1 iff the receiver of transceiver $p$ at node $d_k$ is assigned to $k$ and operates on wavelength $w$.

*Continuous variables:*

- $l(k)$: launch time of $k$.
- $F$: finish time.

*Constraints:*

*1) Wavelength/tranceiver assignment:* For each packet, that is, $\forall k$

$$\sum_w \lambda_w^k = 1 \tag{1}$$

$$\sum_p t_{wp}^k = \lambda_w^k, \forall w \tag{2}$$

$$\sum_p r_{wp}^k = \lambda_w^k, \forall w \tag{3}$$

*2) Link-conflict set constraints:* Two connections overlapping on links have to be either *time-disjoint* or *wavelength-disjoint*. Let $C_l = \{(k, k')\}$ be the *link-conflict set*, that is, $\forall k, k'$, if $k$ and $k'$ share at least one link, then $(k, k') \in C_l$, and vice versa. Thereby, for all such pairs, we enforce time-disjointness *or* wavelength-disjointness. That is, $l(k) + h_k \leq l(k')$ *or* $l(k') + h_{k'} \leq l(k)$ *or* $\lambda_w^k + \lambda_w^{k'} \leq 1$. We translate the logical *OR* correlated constraints to a set of *AND* correlated linear constraints: $\forall (k, k') \in C_l$,

$$l(k) + h_k - l(k') \leq M \cdot x_{kk'} \tag{4}$$

$$l(k') + h_{k'} - l(k) \leq M \cdot x_{k'k} \tag{5}$$

$$\lambda_w^k + \lambda_w^{k'} + x_{kk'} + x_{k'k} \leq 3 \tag{6}$$

where $M$ is a large number, and $x_{kk'}$ is binary and forced to 1 if $k$ finishes after $k'$ starts.

*3) Source/destination conflict set constraints:* Two connections sharing the same source/destination have to be either time-disjoint or *transceiver-disjoint*. Let $C_s^i$ and $C_d^i$ be the *source/destination conflict set* at node $i$, respectively. If $k$ originates/terminates at node $i$, then $k \in C_{s/d}^i$. Applying the same technique as before, we have $\forall i$,

$$\sum_w t_{wp}^k + \sum_w t_{wp}^{k'} + x_{kk'} + x_{k'k} \leq 3, \forall k, k' \in C_s^i \tag{7}$$

$$\sum_w r_{wp}^k + \sum_w r_{wp}^{k'} + x_{kk'} + x_{k'k} \leq 3, \forall k, k' \in C_d^i \tag{8}$$

where $x_{kk'}$ is defined the same as in Eqs. (4) and (5).

*4) Pairing-conflict set constraints:* This constraint only applies to the A/D model. In the formulation for the CDC model, this set of constraints is removed. We define *pairing-conflict set* $C^i$ as, $\forall k, k'$, iff $k$ originates at node $i$ and $k'$ terminates at node $i$, $(k, k') \in C^i$. For such pairs, we have to ensure that, at any point of time, add/drop of the same pair are parked on the same wavelength[1], that is, $\forall i, p$,

$$\sum_w (t_{wp}^k \vee r_{wp}^{k'}) + x_{kk'} + x_{k'k} \leq 3, \forall (k, k') \in C^i \tag{9}$$

*Objective:* The objective is to minimize the finish time, i.e.,

$$\text{Minimize: } F = \max_k \{l(k) + h_k\}$$

[1]The OR clause in Eq. (9) can be linearized by the following generic technique. $A \vee B$ is replaced by a new binary variable $C$, and two additional constraints are added, i.e., $C \geq \frac{A+B}{M}$ and $C < A + B + 1$, where $M$ is a large constant.

## IV. Problem Complexity and Heuristic Approach

We have derived and solved the model for optimal real-time service scheduling in AVATAR using a peer-to-peer traffic model. However, the MILP model does not scale well as the problem size grows. An alternative approach is to devise a fast and near-optimal heuristic to tackle the problem.

### A. Problem Complexity

We outline reductions from *Multi-Processor Scheduling (MPS)* and *Circular-Arc Coloring (CAC)* problem, respectively, to show our problem is NP-hard, and to shed light into the problem's nature. We reduce the MPS problem with $T$ tasks to schedule on $M$ independent processors to a special case of our problem, where $W = P = M$, and there are $T$ packets to be scheduled, and they all initiate, traverse the whole ring, and terminate at the same node. The CAC problem can be reduced to another special case where $W = P = 1$, and the circular arcs become packets with length 1.

### B. Heuristic Design

Now that we understand the problem complexity, we resort to a heuristic algorithm to tackle the general version of the packet-scheduling problem. The heuristic is devised to be simple, fast, near-optimal, and readily applicable to dynamic scenarios, wherein online scheduling of randomly-arriving packets or circuit connections is needed. With these design imperatives in mind, we propose an *Earliest Finish-time, Least Variance (EFLV)* heuristic to schedule packets one-by-one.

EFLV assigns resources based on current network state. We first introduce some variables to capture the network state:

- $E(w, i)$: earliest time to transmit a packet that bypasses node $i$ on wavelength $w$.
- $T_i(w, p)/R_i(w, p)$: earliest time the transmitter/receiver of transceiver $p$ can be used to transmit a packet from/to node $i$ on wavelength $w$.

We elaborate on the algorithm only for the A/D ROADM, since the CDC model requires only minor modifications. Similar to Multi-Processor Scheduling, packets are first sorted in decreasing order of packet length, and then processed one by one. For each packet, EFLV assigns a wavelength, a transmitter/receiver at source/destination respectively, and a continuous time interval. According to the principle of *earliest finish time*, EFLV seeks to assign wavelength that allows earliest start of the packet transmission, that is,

$$l(k) = \min_w \{\min_p T_{s_k}(w, p), \min_p R_{d_k}(w, p), \max_i E(w, i)\} \tag{10}$$

where $i$'s are the nodes bypassed by packet $k$. The time interval allocated is $[l(k), f(k)]$, where $f(k) = l(k) + h_k$. The wavelength that gives the minimum $l(k)$ is assigned to packet $k$.

*Least variance*, on the other hand, implies assigning the transmitter/receiver that, while not exceeding $l(k)$, differs least from $l(k)$, that is,

$$\arg\max_p \{T_{s_k}(w_k, p) \leq l(k)\} \tag{11}$$

$$\arg\max_p \{R_{d_k}(w_k, p) \leq l(k)\} \tag{12}$$

where $w_k$ is the wavelength determined in Eq. (10). The intuition is that, when multiple transceiver pairs are available for the earliest packet transmission, it is desirable to spare those "less loaded" pairs for future allocation, since transceiver resource is relatively scarce.

Following the resource allocation, we need to update $E(w,i)$, $T_i(w,p)$, and $R_i(w,p)$ accordingly. Updates are detailed as follows, $\forall i$ along the path from $s_k$ to $d_k$:

$$E(w_k, i) := f(k) \tag{13}$$

$$T_i(w_k, p) := \max\{f(k), T_i(w_k, p)\}, i \neq d_k, \forall p \tag{14}$$

$$R_i(w_k, p) := \max\{f(k), R_i(w_k, p)\}, i \neq s_k, \forall p \tag{15}$$

Source has some additional updates:

$$T_{s_k}(w, p_k) := \max\{f(k), T_{s_k}(w, p_k)\}, \forall w \tag{16}$$

$$R_{s_k}(w, p_k) := \max\{f(k), R_{s_k}(w, p_k)\}, \forall w \neq w_k \tag{17}$$

Destination is updated similarly. Note that, for the CDC model, transmitter and receiver are decoupled, so we do not need to update the receivers at the source or the transmitters at the destination. The overall algorithm is summarized below.

**Algorithm 1** EFLV

Initialize all $E(w,i)$, $T_i(w,p)$, $R_i(w,p)$ to 0.
Sort the packets in decreasing order w.r.t. $h_k$.
**while** List not empty **do**
  1. Pick the first packet, calculate $l(k)$ in Eq. (10), assign wavelength, transceivers according to Eqs. (10)-(12).
  2. Update $E$, $T$, $R$ according to Eqs. (13)-(17).
  3. Remove the packet from list.
**end while**
Output $\max\{l(k) + h_k\}$ and the wavelength, transceiver assignment for each packet.

## V. Results and Discussions

We start with a small network with low traffic, namely, a 8-node ring with 20 packets to schedule, to verify the mathematical model and performance of the heuristic. Later, the resource tradeoff is more comprehensively demonstrated on a larger network with 16 nodes and 1,000 packets to schedule. The number of optical nodes is expected to be significantly lower than the actual number of various onboard sensors/actuators for two reasons: 1) optical ring architecture rarely deploys more than 16 nodes, 2) each ROADM is connected with a cluster of collocated sensors/actuators, delivering aggregated control traffic. In addition, packet lengths are not subject to standard Ethernet frame length constraint.

The first set of evaluations are conducted on a 8-node ring. The total number of node pairs are 28. 20 is thus a reasonable number to simulate the aggregated traffic. When all packets are transmitted in parallel, the schedule length achieves the minimum, i.e., the finish time of the longest packet transmission $\max_k h_k = 9$. A serialized schedule has length of 109 in the single-channel time-triggered architecture. We compare the scheduling performance under different network configurations determined by the number of wavelengths per link and transceivers per node, and the ROADM technology. Then, we verify the EFLV heuristic against the optimal MILP solution. Finally, we evaluate the design tradeoffs using EFLV on a 16-node network.

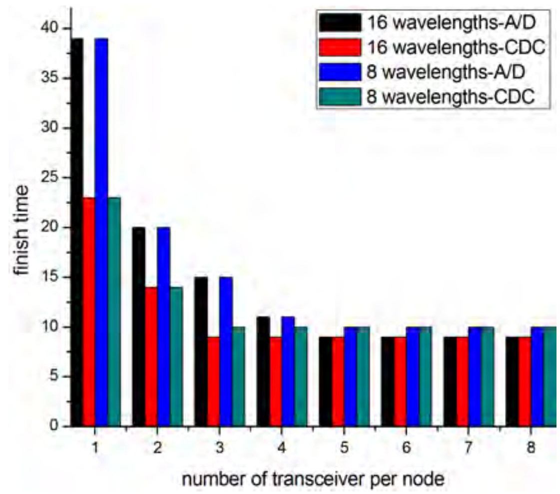



Fig. 6. Comparison of optimal schedule length as a function of $P$.

TABLE I
MILP SOLVING TIME

| network configuration | run time |
|---|---|
| $W = 1, P = 1$ | 5168.45 sec |
| $W = 3, P = 1$ | 11616.82 sec |
| $W = 5, P = 2$ | 17836.86 sec |
| $W = 8, P = 3$ | 172984.09 sec |

### A. MILP Results for Small Network Example

The mathematical model we proposed in this paper nicely captures the various dimensions, namely, time-domain continuity, wavelength continuity, transceiver tunability, into one integrated scheduling formulation. Due to the complexity of the problem itself, solving the MILP by the usual branch-and-bound method to search through the solution space is not scalable as the problem size increases. Here, we report for several problem instances, in Table I, the MILP solving time using ILOG CPLEX 9.0 on Intel(R) Quad Core i5 CPU at 3.20 GHz with 8 GB memory.

In Fig. 6, we fix the number of wavelengths to $W = 16, 8$, and draw finish time as a function of $P$. In all four cases, we observe a decrease of finish time as $P$ increases, which corresponds with the general intuition that "more resources render better performance". For illustration purposes, we take a closer look at the case of A/D ROADM with 16 wavelengths. When $P = 1$, the wavelength resource is over-provisioned. Lack of transceiver resources limits the packets from tapping into the wavelength capacity. When we increase $P$ to 2, finish time is significantly reduced, by about $50\%$. As $P$ further increases, we see an amortized gain as the wavelength has become the limiting resource. In other words, wavelength resources are saturated after a certain point.

CDC ROADM renders better performance compared to A/D ROADM under the same resource configuration. In addition,

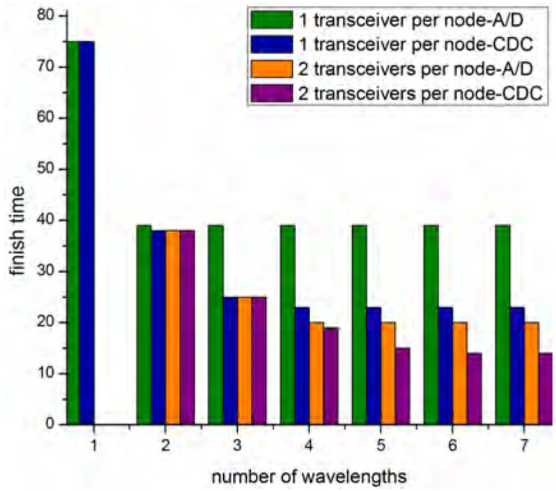
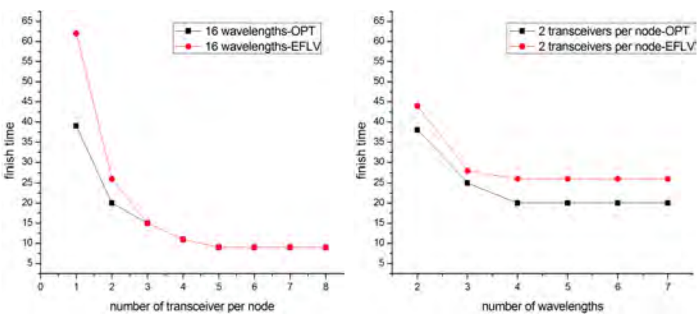



Fig. 7. Comparison of optimal schedule length as a function of $W$.




(a) $F$ as a function of $P$. (b) $F$ as a function of $W$.

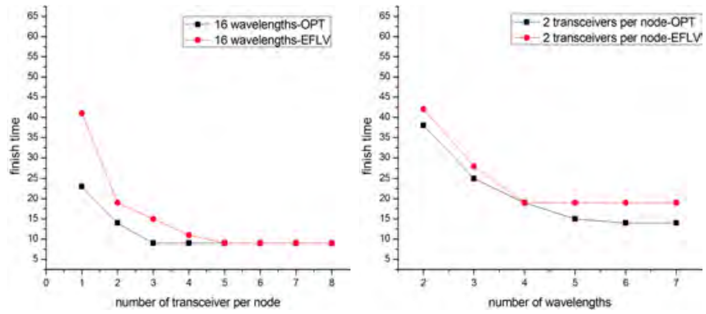
Fig. 8. Comparisons of EFLV and optimum: A/D ROADM model.

the scheduling performance using CDC ROADM converges faster to the lower bound limited by number of transceivers (Fig. 6) or number of wavelengths (Fig. 7). The decoupling of transmitter and receiver in CDC architecture translates to better utilization of transceiver and wavelength resources.

In Fig. 7, we show the interaction between finish time and number of wavelengths, while fixing the number of transceivers per node. $P$ is set to 1 and 2, since in avionics application, a node is not foreseeably to equip more than 2 transceivers. The same observations can be made as in Fig. 6. It is worth noting that, even with a conservative resource configuration ($W = 2$, $P = 1$), which is equivalent to a dual-channel TTP with spatial reuse, AVATAR is able to achieve a decrease in finish time of over $65\%$, i.e., from a single-channel TTP to AVATAR with two wavelength channels.

### *B. Evaluation of EFLV Scheduling for Small Network*

We evaluate the performance of the EFLV heuristic in light of the optimal scheduling generated by solving the MILP. Results for A/D and CDC ROADM model are shown in Figs. 8 and 9, respectively. In particular, Fig. 8(a) draws the comparison by varying $P$, while Fig. 8(b) of varying $W$. The EFLV heuristic in most cases gives optimal or close-to-optimal scheduling. The one exception lies in the case of $P = 1$. Scheduling performance in this case is largely limited




(a) $F$ as a function of $P$. (b) $F$ as a function of $W$.

Fig. 9. Comparisons of EFLV and optimum: CDC ROADM model.

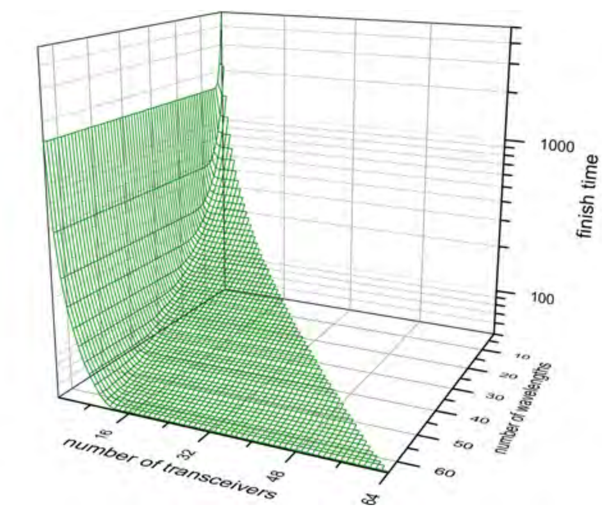



Fig. 10. EFLV scheduling using A/D ROADM.

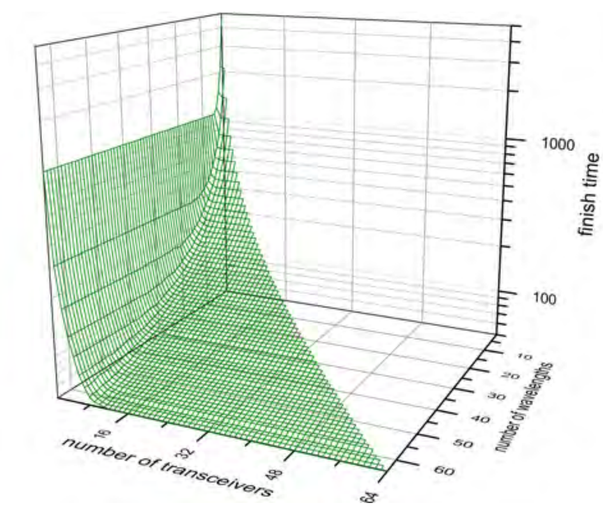



Fig. 11. EFLV scheduling using CDC ROADM.

by transceiver resource. It is intuitive that constrained resource configuration requires more scheduling sophistication.

### *C. Heuristic Solution for Large Network Example*

Due to the high computational cost of solving the MILP for our problem and near-optimality of EFLV scheduling, we use

EFLV to draw finish time as a function of both wavelengths ($1 \leq W \leq 64$) and transceivers ($1 \leq P \leq W$), shown in Figs. 10 and 11, for a 16-node ring with 1,000 packets to schedule. For lack of field data, we adopt a probabilistic traffic model for the general peer-to-peer, distributed system where traffic is uniformly distributed among all possible source-destination pairs. With serial scheduling in TTP architecture, the finish time is given by $\sum h_k = 5369$. In the performance charts, we see that both ROADM models exhibit largely the same resource tradeoff. And the observations accord with the MILP results. The peaks of the 3-D surface for both models are of case $W = 1, P = 1$. In this case, AVATAR is reduced to single-channel TTP with spatial reuse. The finish time decreases by about $20\%$ to $4601$. In this base case particularly, the CDC model is equivalent to the A/D model. Significant reduction in finish time is observed with immediate increase of resources to the base case. Further increase of resources results in an amortized gain. CDC model generally outperforms the A/D model under same resource configurations for its additional flexibility of transceivers. With the same number of transceiver pairs at each node, CDC model can better utilize the wavelength resources. In effect, the finish time converges at higher number of wavelengths. From a design perspective, investing in $W = P$ is almost always a bad choice. The finish time, for a given number of wavelengths, usually converges at a much lower count of transceivers. Not only design, but upgrade can also benefit from these performance charts. For example, given a budget and resource price model, multiple resource upgrade combinations are possible. A simple decision could be the one that yields the steepest descent of finish time.

## VI. Conclusion

We proposed AVATAR based on an optical WDM ring as a future promising aero-engine control network architecture. Sophisticated packet scheduling schemes were developed to exploit the vast capacity provided by WDM technology to support real-time avionic services. The scheduling problem was first abstracted as an MILP for two different ROADM architectures, namely, Add/Drop pair (A/D) model and Colorless, Directionless, Contentionless (CDC) model. The CDC ROADM architecture removes the pairing constraint and results in a more relaxed formulation. A simple scheduling heuristic Earliest Finish-time, Least Variance (EFLV) was also proposed to tackle the problem. EFLV was shown to achieve near-optimal scheduling in both ROADM models.

The superiority of AVATAR over Time-Triggered Protocol (TTP) architecture in avionic application was demonstrated conceptually and quantitatively via extensive numerical evaluations. Even with very conservative resource configuration, AVATAR was shown to achieve more than $65\%$ temporal efficiency compared to TTP (i.e., more than twice of the traffic can be accommodated). Tradeoffs between spatial resources (wavelength and transceivers) and temporal performance (finish time) were captured in the numerical diagrams to consult the design parameter selection of AVATAR.

## References


[1] D. E. Culley and A. R. Behbahani, "Communication needs assessment for distributed turbine engine control," Glenn Research Center, Cleveland, OH, Tech. Rep. NASA/TM-2008-215419, Sep. 2008.

[2] M. Xia, B. Moslehi, B. Mukherjee, A. R. Behbahani, and R. Miller, "CORIN/DORIN: A WDM-enabled platform for aero-engine control systems," in *Proc. IEEE AVFOP'08*, San Diego, CA, Sep. 2008, pp. 77–78.

[3] R. Wang, R. J. Black, B. Moslehi, A. R. Behbahani, and B. Mukherjee, "Lightweight optical aero-engine control network," in *Proc. IEEE/OSA OFC'11*, Los Angeles, CA, Mar. 2011, p. OThZ4.

[4] J. G. Zhang, A. Pervez, and A. B. Sharma, "Avionics data buses: an overview," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 18, no. 2, pp. 18–22, Feb. 2003.

[5] D. N. Harres, "Military aircraft fiber optics networks: status and direction," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 19, no. 6, pp. 16–22, June 2004.

[6] S. F. Habiby and R. Vaidyanathan, "WDM optical backbone networks in aircraft applications: Networking challenges and standards progress," in *Proc. IEEE MILCOM'09*, Boston, MA, Oct. 2009, pp. 1–6.

[7] S. F. Habiby and M. J. Hackert, "Ronia results: WDM-based optical networks in aircraft applications," in *Proc. IEEE AVFOP'08*, San Diego, CA, Sep. 2008, pp. 71–72.

[8] S. F. Habiby and R. Dutt, "Optical network architecture, technology and component challenges in aircraft network applications," in *Proc. IEEE AVFOP'09*, San Antonio, TX, Sep. 2009, pp. 62–63.

[9] J. Wu *et al.*, "Distributed fiber optic gas sensing for harsh environment," GE Global Research, Niskayuna, NY, Tech. Rep. DE-FC26-05NT42438, June 2008.

[10] L. Liu, X. Li, P.-J. Wan, and O. Frieder, "Wavelength assignment in WDM rings to minimize SONET ADMs," in *Proc. IEEE INFOCOM'00*, vol. 2, Tel Aviv, Israel, Mar. 2000, pp. 1020–1025.

[11] X. Zhang and C. Qiao, "On scheduling all-to-all personalized connection and cost-effective designs in WDM rings," *IEEE/ACM Trans. Netw.*, vol. 7, no. 3, pp. 435–445, June 1999.

[12] A. L. Chiu and E. H. Modiano, "Traffic grooming algorithms for reducing electronic multiplexing costs in WDM ring networks," *J. Lightw. Technol.*, vol. 18, no. 1, pp. 2–12, Jan. 2000.

[13] O. Gerstel, R. Ramaswami, and G. H. Sasaki, "Cost-effective traffic grooming in WDM rings," *IEEE/ACM Trans. Netw.*, vol. 8, no. 5, pp. 618–630, Oct. 2000.

[14] X. Zhang and C. Qiao, "An effective and comprehensive approach for traffic grooming and wavelength assignment in SONET/WDM rings," *IEEE/ACM Trans. Netw.*, vol. 8, no. 5, pp. 608–617, Oct. 2000.

[15] J.-C. Bermond and D. Coudert, "Traffic grooming in unidirectional WDM ring networks using design theory," in *Proc. IEEE ICC'03*, vol. 2, May 2003, pp. 1402–1406.

[16] J. Wang, W. Cho, V. R. Vemuri, and B. Mukherjee, "Improved approaches for cost-effective traffic grooming in WDM ring networks: ILP formulations and single-hop and multihop connections," *J. Lightw. Technol.*, vol. 19, no. 11, pp. 1645–1653, Nov. 2001.

[17] K. Lee and K.-Y. Siu, "On the reconfigurability of single-hub WDM ring networks," *IEEE/ACM Trans. Netw.*, vol. 11, no. 2, pp. 273–284, Apr. 2003.

[18] R. Dutta and G. N. Rouskas, "Traffic grooming in WDM networks: past and future," *IEEE Netw.*, vol. 16, no. 6, pp. 46–56, Nov./Dec. 2002.

[19] E. Modiano and P. J. lin, "Traffic grooming in WDM networks," *IEEE Commun. Mag.*, vol. 39, no. 7, pp. 124–129, July 2001.

[20] Y. C. Cheng and T. G. Robertazzi, "Distributed computation with communication delay (distributed intelligent sensor networks)," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 24, no. 6, pp. 700–712, Nov. 1988.

[21] J. Sohn and T. G. Robertazzi, "Optimal divisible job load sharing for bus networks," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 32, no. 1, pp. 34–40, Jan. 1996.

[22] ——, "Optimal time-varying load sharing for divisible loads," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 34, no. 3, pp. 907–923, July 1998.

[23] H. Kopetz and G. Bauer, "The time-triggered architecture," *Proc. IEEE*, vol. 91, no. 1, pp. 112–126, Jan. 2003.

[24] H. Kopetz, "The rationale for time-triggered ethernet," in *Proc. Real-Time Systems Symposium, 2008*, Barcelona, Nov. 2008, pp. 3–11.

[25] H. Kopetz, A. Ademaj, P. Grillinger, and K. Steinhammer, "The time-triggered ethernet (TTE) design," in *Proc. IEEE ISORC'05*, May 2005, pp. 22–33.

[26] D. A. Gwaltney and J. M. Briscoe, “Comparison of communication architectures for spacecraft modular avionics systems,” Marshall Space Flight Center, Huntsville, AL, Tech. Rep. NASA/TM-2006-214431, June 2006.

[27] L. M. Parrilla, A. L. Rodriguez, A. Simon-Muela, and M. M. Prats, “Design of a middleware interface for ARINC 429 data bus,” *IEEE Trans. Aerosp. Electron. Syst.*, vol. 48, no. 2, pp. 1136–1149, Apr. 2008.

**Rui Wang** Rui Wang is currently a Ph.D. candidate in the Department of Computer Science at the University of California, Davis. He received the B.Eng. in electrical engineering from Shanghai Jiao Tong University (2009) and M.S. in computer science from University of California, Davis (2010). He was a visiting student at the University of New Mexico from August 2008 to December 2008. He worked as a network engineer at AT&T Labs in San Ramon, California from June 2011 to September 2011. He is the winner of the Best Student Paper Award at the 17th International Conference on Optical Networking Design and Modeling (ONDM) 2013.


**Richard J. Black** (M‘84, SM‘09) received the B.Sc. (Hons.) degree in physics from the University of Canterbury, Christchurch, New Zealand, and the Ph.D. degree in fiber optics from the Research School of Physical Sciences, Australian National University, Canberra, Australia. He is a Founding Member and Chief Scientist at Intelligent Fiber Optic Systems Corporation (IFOS), Santa Clara, CA. He is a Technical Program Chair of IEEE ICAIT 2013. His research interests include optical fiber sensing systems with application to medical devices, robotics and medical devices. Dr. Black is a life member of the Optical Society of America, the American Institute of Aeronautics and Astronautics, the International Society for Optical Engineers and ASM International (The Materials Information Society).

**Behzad Moslehi** (M‘84, SM‘98) received the B.S. degree in electrical engineering, in 1978, from Arya-Mehr University of Technology, Tehran, Iran, and the M.S. degree in electrical engineering, in 1980, the M.S. degree in applied physics, and the Ph.D. degree in engineering, in 1984, from Stanford University, Stanford, CA. He is the Founder and Chief Executive Officer/Chief Technology Officer of Intelligent Fiber Optic Systems Corporation (IFOS), Santa Clara, CA. His current research interests include photonic signal processing, sensing, communications, and networking for applications in avionics, safety, life sciences, and energy. Dr. Moslehi is a Senior Member of the Optical Society of America, the International Society for Optical Engineers, the Society for the Advancement of Material and Process Engineering, the Society of Petroleum Engineers, the American Wind Energy Association, and Sigma Xi.

**Alireza (Al) Behbahani** is the Senior Aerospace Engineer and Group Leader for the Advanced Integrated Controls And Prognostic / Diagnostic Systems Group at the Propulsion Directorate - Turbine Engine Division at the Air Force Research Laboratory (AFRL) in Wright Patterson Air Force Base (WPAFB), OH. He has a B.S.E.E. from Utah State, and an M.S. and a Ph.D. from the Ohio State University. Dr. Behbahani’s career of over 35 years includes highly cited research contributions and significant professional service, industrial, teaching, and program management experience in Control Systems. He is a SPRDE Level III Certified and has been involved in pioneering work on Distributed Engine controls, where he is currently managing an AFRL funded program in High Temperature Distributed Engine Controls with the DECWG. His research interests include intelligent controls, FADEC, PHM, LEC, MBC, intelligent sensors and actuators, M&S of gas turbine, controls-related research, development, integration, and testing. At the AFRL, he manages several programs related to control systems, PHM, modeling, simulation, controls-related research, development, integration, and testing, engine health management research including the development of topical models, algorithms, and health management strategies related to FADEC at AFRL. He is the Controls IPT Lead for ADVENT for both GE and Rolls-Royce/LibertyWorks, Controls IPT Lead for AETD/GE Program,, and also involved with VCAT, AATE, JSF related projects, VAATE, NRC, SBIR, STTR, and other funded projects in Controls and EHM underway in industry. Previously he was the Project Leader / Lead Engineer / Certified Six Sigma / Certified ISO 9001- CF6 Control Systems, Commercial Control Systems - Controls, Center of Excellence at the General Electric Aircraft Engines, Evendale, OH.

**Biswanath Mukherjee** (S‘82, M‘87, SM‘05, F‘07) is Distinguished Professor at University of California, Davis, where was Chairman of Computer Science during 1997-2000. He received the B.Tech. degree from Indian Institute of Technology, Kharagpur (1980) and Ph.D. from University of Washington, Seattle (1987). He was General Co-Chair of the IEEE/OSA Optical Fiber Communications (OFC) Conference 2011, Technical Program Co-Chair of OFC2009, and Technical Program Chair of the IEEE INFOCOM96 conference. He is Editor of Springers Optical Networks Book Series. He has served on eight journal editorial boards, most notably IEEE/ACM Transactions on Networking and IEEE Network. In addition, he has Guest Edited Special Issues of Proceedings of the IEEE, IEEE/OSA Journal of Lightwave Technology, IEEE Journal on Selected Areas in Communications, and IEEE Communications. He has supervised over 50 PhDs to completion and currently mentors a dozen advisees, mainly PhD students. He is co-winner of Optical Networking Symposium Best Paper Awards at IEEE Globecom 2007 and 2008. He is author of the graduate-level textbook Optical WDM Networks (Springer, January 2006). He served a 5-year term on Board of Directors of IPLocks, a Silicon Valley startup company. He has served on Technical Advisory Board of several startup companies, including Teknovus (acquired by Broadcom)), Intelligent Fiber Optic Systems Corporation (IFOS), and LookAhead Decisions Inc. (LDI).