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Drive to miniaturization: integrated optical networks on mobile platforms

Michael M. Salour · Marwan Batayneh · Luis Figueroa

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Abstract With rapid growth of the Internet, bandwidth demand for data traffic is continuing to explode. In addition, emerging and future applications are becoming more and more network centric. With the proliferation of data communication platforms and data-intensive applications (e.g. cloud computing), high-bandwidth materials such as video clips dominating the Internet, and social networking tools, a networking technology is very desirable which can scale the Internet's capability (particularly its bandwidth) by two to three orders of magnitude. As the limits of Moore's law are approached, optical mesh networks based on wavelength-division multiplexing (WDM) have the ability to satisfy the large- and scalable-bandwidth requirements of our future backbone telecommunication networks. In addition, this trend is also affecting other special-purpose systems in applications such as mobile platforms, automobiles, aircraft, ships, tanks, and micro unmanned air vehicles (UAVs) which are becoming independent systems roaming the sky while sensing data, processing, making decisions, and even communicating and networking with other heterogeneous systems. Recently, WDM optical technologies have seen advances in its transmission speeds, switching technologies, routing protocols, and control systems. Such advances have made WDM optical technology an appealing choice for the design of future Internet architectures. Along these lines, scientists across the entire spectrum of the network architectures from physical layer to applications have been working on developing devices and communication protocols which can take full advantage of the rapid advances in WDM technology. Nevertheless, the focus has always been on large-scale telecommunication networks that span hundreds and even thousands of miles. Given these advances, we investigate the vision and applicability of integrating the traditionally large-scale WDM optical networks into miniaturized mobile platforms such as UAVs. We explain the benefits of WDM optical technology for these applications. We also describe some of the limitations of WDM optical networks as the size of a vehicle gets smaller, such as in micro-UAVs, and study the miniaturization and communication system limitations in such environments.

1 Introduction

The world we live in is in the midst of a digital revolution and more recently an exploding mobile revolution. Today's telecommunication networks are incredibly complex systems that link millions of computers and billions of telephones around the globe, and they are mediating more and more aspects of our daily lives. There is a growing need for scalable and cost-effective high-speed telecommunication network technologies, as existing technologies are incapable of supporting the enormous growth in traffic that will result from the rapidly growing use of high-bandwidth applications, such as video-on-demand, music-on-demand, video conferencing, broadband smart phones, etc. In this context, wavelength-division multiplexing (WDM) [1] optical networking technology enables us to dramatically scale up the network capacity at affordable cost without increasing the electronic switching speed which is essential for meeting the heterogeneous requirements of future applications and services.

M.M. Salour (✉) · M. Batayneh · L. Figueroa
IPITEK, Inc, 2330 Faraday Avenue, Carlsbad, CA 92008-7216,
USA
e-mail: mmsalour@ipitek.com

M.M. Salour
FlyByLight, LLC, P.O. Box 130878, Carlsbad, CA 92013-0878,
USA

Over the years, WDM optical technology has significantly advanced. Today WDM-based optical links can provide terabits of information in an optical fiber. The motivation of using WDM optical networks in large-scale telecommunication networks spanning cities, metro areas, countries, or even continents has been fueled by the massive explosion of end-user applications. After a quick look at these applications, we find that they are based on the proliferation of highly integrated systems that allow huge processing as well as communication to take place on a single small platform such as a smart phone. Today's mobile phone systems allow phone service, Internet access, video viewing and download, text messaging, data storage, etc. However, these systems are primarily based on microelectronic circuits. It is believed today that the reduction in size, power consumption, and integration of electronics is at a critical stage where the level of integration may no longer be able to scale with Moore's law. Moore's law describes a trend in evolution of computation systems. Specifically, it states that the number of transistors that can be placed on an integrated circuit can double approximately every two years. Therefore, there have been tremendous activities for developing new technologies that can scale or even exceed technology growth as predicted by Moore's law. For example, nanolevel technologies (simply nanotechnology) that involve the extensions of current conventional device physics from micro- to nanolevels are being investigated [2]. There are also activities that involve developing new methods such as molecular technology, nanophotonics, as well as developing materials at the nanoscale. While nanotechnology is a term used to describe the technology in which systems are built on elements at the nanoscale, several approaches are being investigated with different advantages, risk factors, limitations, and potential success rates. For example, molecular nanotechnology is concerned with developing nanosystems that are operating on the molecular scale and in some cases mimic biological systems. It is associated with the molecular assembly in which the system is produced by manipulating the molecules to produce the desired structure or machine. One of the curious aspects of biological systems is the massive degree of multiplexing that is found for the transmission of information in order to compensate for the relatively slow individual channel connections.

With miniaturization in mind, we focus our attention on the case of integrating miniaturized WDM optical networks into mobile platforms as the fundamental communication architecture in these systems. We study the benefits of WDM optical technology for such applications. We also explain the communication constraints in WDM optical networks and how these constraints impact the overall system design and the miniaturization of optical networks for mobile platforms. Moreover, we explain several limiting factors that impact the miniaturization of optical networks. We believe that such application-specific parameters must be well understood in order to design and optimize small-size communication frameworks using WDM optical technology.

The rest of the paper is organized as follows. Section 2 explains the architectural elements of conventional WDM optical networks, i.e. WDM optical networks used in metro and wide-area telecommunication networks. Section 3 discusses information communication constraints in WDM optical networks and introduces a mathematical model that captures these constraints. Section 4 investigates the benefits of using WDM optical technology for mobile platforms with particular emphasis on its application in air vehicles (e.g. aircraft). In Sect. 5, we study several enabling technologies and technical limitations of WDM optical network miniaturization and application in certain mobile environments. We look at the node architecture and formally state the problem. Section 6 provides an overview of a hybrid approach that exploits several technologies for achieving a more optimal system design which requires understanding of various design factors and tradeoffs. In Sect. 7, we provide a brief summary of the communication limits facing unmanned mobile platforms, and suggest some techniques for improving their performance. Finally, Sect. 8 provides a summary.

2 Overview of WDM optical networks

Due to its enormous capacity and flexibility, optical fiber technology is used in telecommunication networks. An optical fiber contains multiple channels each using a different wavelength of light which can have high capacities of 10 Gbps, 40 Gbps, or even 100 Gbps.

In conventional optical networks, wavelength-division multiplexing (WDM) is a technology that is widely used to multiplex multiple optical signals in a single optical fiber using different wavelengths. WDM technology relies on the fact that optical fibers can carry many wavelengths of light simultaneously without interaction between each wavelength. Thus, a single fiber can carry many separate wavelength signals or channels simultaneously. Each of these wavelength channels can be pulsed or modulated at rates of up to 10 Gbps (and even 40 and 100 Gbps are being experimented with). In a WDM optical network, light signals (called light paths) create the connectivity between any two nodes. A light path may span several optical-fiber links and, on each link, it uses one wavelength channel. Today, the advances in WDM optical technology enable the network to have mixed line rates (MLRs), i.e. different links may operate at different rates; also, a link may have optical channels that operate at different rates (10/40/100 Gbps).

To explain the fundamental operation of WDM optical networks, consider the simple case of a point-to-point (P2P) WDM system involving two locations as shown in Fig. 1.

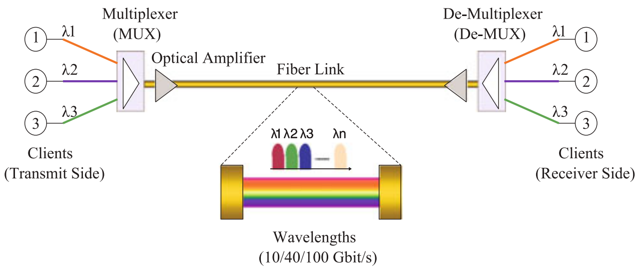

Fig. 1 P2P WDM optical link

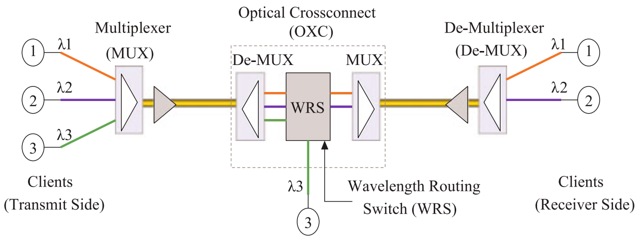

Fig. 2 Simple WDM optical network with intermediate wavelength routing

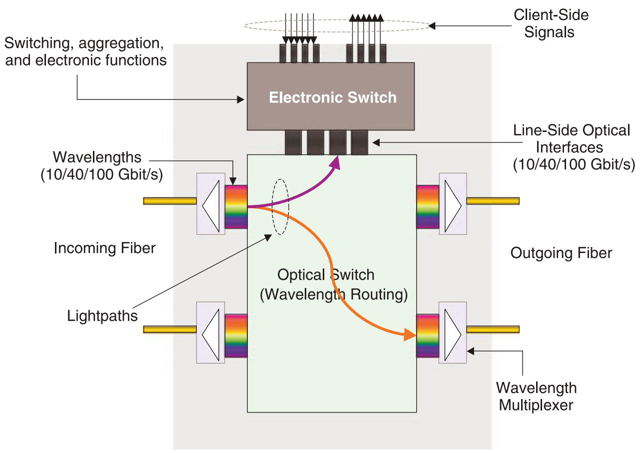

Fig. 3 Node architecture for WDM optical mesh networks

Moreover, Fig. 2 shows a three-location WDM optical network. As the figure shows, the traffic originating at one location is designated for two different locations. In this case, since some of the client traffic needs to be dropped at the intermediate location, we need to use a system that intersects the fiber signal, decomposes the light paths, and determines their intended destinations. These systems are called optical switches.

Therefore, in practical networks, optical switches known as optical cross-connects (OXCs) provide the switching and routing functions for supporting the logical data connections between client subnetworks. OXCs are used for performing wavelength-level routing. An OXC takes in an optical signal at each of the wavelengths at an input port, and can switch it to a particular output port, independent of the other wavelengths. Normally, OXCs are combined with wavelength multiplexers (MUX) and demultiplexers (de-MUX) to allow for packing and unpacking of optical channels into/from the fiber link for transmission. Internally, an OXC uses a wavelength routing switch (WRS) which together with MUX and de-MUX form the OXC system. Thus, an OXC can cross-connect the different wavelengths from the input to the output, where the connection pattern of each wavelength is independent of the others. By appropriately configuring the OXCs along the physical path, logical connections (i.e. light paths) can be established among network nodes. Finally, Fig. 3 shows a WDM optical node architecture that can be used in a WDM optical mesh communication network [3]. It has two components: (1) an optical cross-connect (OXC) which performs switching at the light path level and (2) an electronic switch (ES). ES initiates and terminates the light path using application-specific interfaces, namely transmitters and receivers. ES also performs electronic functions of grooming connections onto light paths.

Optical technologies have been the workhorse that enabled high-speed data communication networks. In addition, the introduction of WDM technology has elevated optical networks by allowing several optical channels to coexist in a single fiber, which increased the capacity of a network by orders of magnitude. Therefore, and given this big success and penetration of WDM optical networks, we believe that the next wave of evolution will be in taking a WDM optical network from its ‘conventional’ environment of a telecommunication network application into micro-scale platforms. Based on today’s applications, the amount of capacity that a WDM optical network provides may initially seem very high for current small systems (e.g. unmanned air vehicles (UAVs)) to deploy. Nevertheless, we believe that such micro-systems are increasingly penetrating many applications. Moreover, the advances of their enabling technologies have been leading to developing more sophisticated and more capable micro-scale systems. This trend is fiercely continuing. Hence, there is no doubt that such systems will have a critical role in future dynamic communication applications which will require huge bandwidth requirements while maintaining their miniature size requirements.

3 Communication constraints in optical networks

Now that we know the architectural elements of WDM optical networks, it is essential to consider the communication and networking aspects of a WDM optical network. This analysis is very critical in identifying overall network design decisions and how those impact the miniaturization of optical networks.

In WDM optical mesh networks (Fig. 4), a light path is implemented by selecting a path of physical links be-

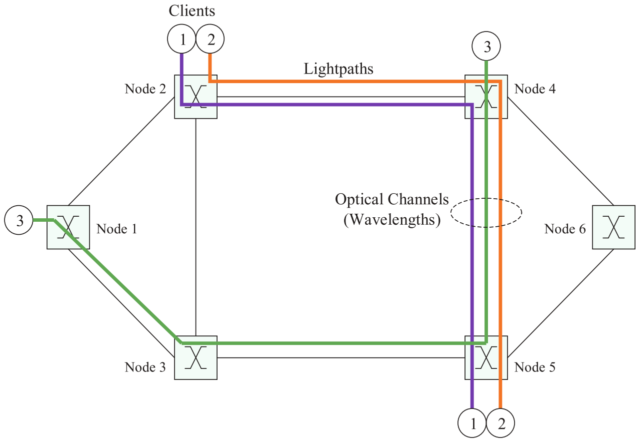

Fig. 4 Example WDM optical mesh network

tween the source and destination edge nodes, and reserving a particular wavelength on each of these links for the light path. Thus, in establishing an optical connection we must determine the routing (i.e. finding a path over the fiber links) and determine a wavelength channel (known as wavelength assignment) for the light path. The overall problem is known as the routing and wavelength assignment (RWA) problem [1], which is the classical underpinning problem for routing in optical networks.

The additional complexity of the RWA arises from the following two constraints.

- Wavelength continuity constraint: a light path must use the same wavelength on all the links along its path from the source to the destination node.
- Distinct wavelength constraint: all light paths using the same link (fiber) must be allocated distinct wavelengths.

However, since an optical network can support multiple rates from 1 Gbps to 100 Gbps and even Tbps in the future, the routing becomes more complex due to the addition of the following constraints.

- A light path must only use one rate along its path. We call this the single rate assignment constraint.
- If a light path originating from node X and destined to node Z (lightpath$_{XY}$) uses links X–Y and Y–Z, where link X–Y is running at a rate R_1 and link Y–Z is running at a different rate R_2, then the light path must be segmented into two light paths, namely, lightpath$_{XY}$ and lightpath$_{YZ}$. In this case, lightpath$_{XY}$ runs at rate R_1 and lightpath$_{YZ}$ runs at rate R_2. We call this the rate continuity constraint.

Note that the wavelength continuity constraint can be relaxed if the OXCs use wavelength converters. A wavelength converter is an optical device that converts the input wavelength to a different wavelength at the output of the device. This simplifies the design of the network. However, it introduces the complexity of using new components in the system, which incurs other limitations.

Next, we present the mathematical optimization model for the routing architecture in WDM optical networks which is based on the integer linear programming (ILP) model.

First, we introduce the notation used in the formulation.

n	node n.
sd	source and destination of a communication channel (connection).
ij	originating and terminating ends of a light path.
mn	originating and terminating ends of an optical link.
w	wavelength channel w.
r	transmission rate of the optical channel.
y	bandwidth requirement of the communication channel.
z	index of a communication channel with certain granularity. This allows for running multiple communication sessions with the same type and rate. Note that these sessions can use different paths.
Δ_n	degree of node n, i.e. the number of fiber links connected to node n.

Communication inputs (system parameters)

- S^n = number of interface slots at node n. This parameter determines the maximum number of electronic communication interfaces (cards) that can physically be used in an optical node.
- W_{mn} = number of wavelength channels on link (m, n). Note that different fiber links can have different channel counts.
- TH = throughput of a node, which reflects the node's maximum capacity.

Communication variables

- Boolean variable, $\alpha_{ij,mn}^{r,w}$, which is equal to 1 if a light path between nodes (i, j) is using wavelength w on link (m, n) and is running at rate r Gbps.
- Integer variable, $\alpha_{ij}^{r,w}$, is the number of light paths between node pair (i, j) using wavelength w on different links and running at rate r Gbps.
- Integer variable, α^r, is the total number of established light paths running at rate r Gbps.
- Boolean variable, $c_{ij}^{sd,y,z}$, which is equal to 1 if the zth connection (s, d) with granularity y is using a light path connecting node pair (i, j).
- Integer variable, T^n, is the number of transmitters used at node n.
- Integer variable, R^n, is the number of receivers used at node n.

Communication constraints

Equation (1) ensures that a wavelength channel w on a link (m, n) can only be used by a single light path and can only run at a single rate.

$$\forall w, \forall mn: \quad \sum_{r} \sum_{i,j} \left(\alpha_{ij,mn}^{r,w}\right) \leq 1. \tag{1}$$

Equations (2) and (3) ensure that the number of light paths using wavelength w and rate r between nodes i and j cannot exceed the number of link-disjoint paths between nodes i and j. They also ensure that any two light paths between nodes i and j using wavelength w and rate r are using two different paths and two different path indexes

$$\forall ij, \forall r, \forall w: \quad \sum_{im \in Links} \left(\alpha_{ij,im}^{r,w}\right) \leq \Delta_i, \tag{2}$$

$$\forall ij, \forall r, \forall w: \quad \sum_{nj \in Links} \left(\alpha_{ij,nj}^{r,w}\right) \leq \Delta_j. \tag{3}$$

Equations (4) and (5) model the number of light paths using wavelength w and running at rate r between nodes i and j. This model is used to ensure meeting other constraints in the system. For example, to ensure that an optical node does not transmit and receive data more than its capacity

$$\forall ij, \forall r, \forall w: \quad \sum_{mj \in Links} \left(\alpha_{ij,mj}^{r,w}\right) = \alpha_{ij}^{r,w}, \tag{4}$$

$$\forall ij, \forall r, \forall w: \quad \sum_{in \in Links} \left(\alpha_{ij,in}^{r,w}\right) = \alpha_{ij}^{r,w}. \tag{5}$$

Equation (6) ensures loopless routing of light paths across link (m, n)

$$\forall ij, \forall mn, \forall r, \forall w: \quad \alpha_{ij,mn}^{r,w} + \alpha_{ij,nm}^{r,w} \leq 1. \tag{6}$$

Equation (7) ensures that the number of wavelength channels used at link (m, n) does not exceed the total number of wavelength channels on the link.

$$\forall mn: \sum_{r} \sum_{ij} \sum_{w} \left(\alpha_{ij,mn}^{r,w}\right) \leq W_{mn}. \tag{7}$$

Equation (8) ensures wavelength/rate continuity for all light paths

$$\forall k \neq (i, j), \forall ij, \forall r, \forall w: \\ \sum_{mk \in Links, m \neq j} \left(\alpha_{ij,mk}^{r,w}\right) = \sum_{kn \in Links, n \neq i} \left(\alpha_{ij,kn}^{r,w}\right). \tag{8}$$

Equations (9), (10), (11), and (12) ensure that the number/rates of light paths between nodes i and j cannot exceed the total number of interface slots or the nodes' throughput (TH).

$$\forall n: \quad \sum_{j} \sum_{w} \sum_{r} \left(\alpha_{nj}^{r,w}\right) \leq T^n, \tag{9}$$

$$\forall n: \quad \sum_{i} \sum_{w} \sum_{r} \left(\alpha_{in}^{r,w}\right) \leq R^n, \tag{10}$$

$$\forall n: \quad T^n + R^n \leq S^n, \tag{11}$$

$$\forall n: \quad \sum_{r} \sum_{j} \sum_{w} \left(r \times \alpha_{nj}^{r,w}\right) + \sum_{r} \sum_{i} \sum_{w} \left(r \times \alpha_{in}^{r,w}\right) \leq \mathrm{TH}. \tag{12}$$

Equations (13), (14), (15), (16), and (17) are the connection over light path routing constraints.

Equations (13) and (14) ensure that the connection must be provisioned by setting the connection Boolean variable to 1

$$\forall sd, \forall y, \forall z: \quad \sum_{i} \left(c_{id}^{sd,y,z}\right) = 1, \tag{13}$$

$$\forall sd, \forall y, \forall z: \quad \sum_{j} \left(c_{sj}^{sd,y,z}\right) = 1. \tag{14}$$

Equations (15) and (16) ensure that the connection must be looped back to its original source by setting the connection Boolean variable to 0

$$\forall sd, \forall y, \forall z: \quad \sum_{i} \left(c_{is}^{sd,y,z}\right) = 0, \tag{15}$$

$$\forall sd, \forall y, \forall z: \quad \sum_{j} \left(c_{dj}^{sd,y,z}\right) = 0. \tag{16}$$

Equation (17) ensures loopless routing of a connection over a light path

$$\forall k \neq (s, d), \forall sd, \forall y, \forall z: \quad \sum_{i} \left(c_{ik}^{sd,y,z}\right) = \sum_{j} \left(\lambda_{kj}^{sd,y,z}\right). \tag{17}$$

Equation (18) ensures that the aggregate bandwidth requirements of all the connections using a light path should not exceed the capacity of that light path

$$\forall ij: \quad \sum_{sd} \sum_{y} \sum_{z} \left(y \times \lambda_{ij}^{sd,y,z}\right) \leq \sum_{r} \sum_{w} \left(r \times \alpha_{ij}^{r,w}\right). \tag{18}$$

Several optimization objectives can be achieved using the previous mathematical model for optical-signal routing. For example, the objective function can minimize the cost of the overall network based on the rates and the number of interfaces used (which is directly proportional to the number of the established light paths). This is shown in (19), where μ^r is the cost of the electronic processing of light paths at rate r

$$\text{Minimize} \sum_{r} \left(\mu^r \times \alpha^r\right). \tag{19}$$

Note that the total number of light paths running at rate r is given by (20)

$$\forall r: \quad \alpha^{r} = \sum_{ij} \sum_{w} \left(\alpha_{ij}^{r,w}\right). \tag{20}$$

Depending on the application-specific limitations, the model can be modified to reflect various design parameters. For example, if component weight or power consumption is an issue for the application, then the model can yield the optimal system design for that given application design objective.

4 The future vision: optical networks on mobile platforms

The integration of WDM optical networks in miniaturized mobile systems could lead to significant performance enhancements [4]. For example, a WDM optical network can replace the conventional communication approaches used in surveillance aircraft to enhance the imagery and sensor fusion capabilities, in addition to making the platforms more scalable and upgradable.

Figure 5 shows a typical aircraft communication architecture. In this architecture, the aircraft's subsystems that control the various aircraft functions are connected using electrical point-to-point (P2P) links that are designed for the specific data and communication protocols used. Moreover, since the communication is primarily built using P2P links, adding new subsystems or adding redundant links is a complex task since it requires re-engineering the physical paths in the aircraft. Also, adding new data formats or communication protocols may require significant changes. Therefore, this communication architecture suffers from scalability and reliability issues.

Now consider Fig. 6, which shows an aircraft using a WDM optical network as its communication architecture. In this architecture, the aircraft's subsystems that control the various aircraft functions are connected using an optical network composed of fiber links and optical switches (OXCs). This architecture can link any subsystem to any subsystem on demand. In this case, adding new subsystems or adding redundant paths does not require re-engineering the physical network since it can easily be achieved by adding logical optical connections (e.g. light paths). Also, adding new data formats or communication protocols is possible since WDM optical technology is transparent to bit rate and signal format. Moreover, adding redundant paths is also simple.

Another important application of miniaturized WDM optical networks is the developing of future unmanned aerial vehicles or UAVs. UAVs use aerodynamic forces to provide vehicle lift and can fly autonomously or are piloted remotely. Currently, most of UAV applications are for military purposes where they perform reconnaissance as well as various attack missions. Nevertheless, UAVs are also used in a small but growing number of civil applications.

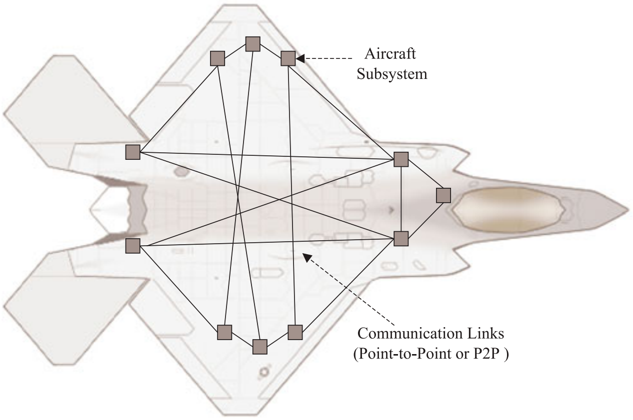

Fig. 5 Aircraft's typical communication architecture

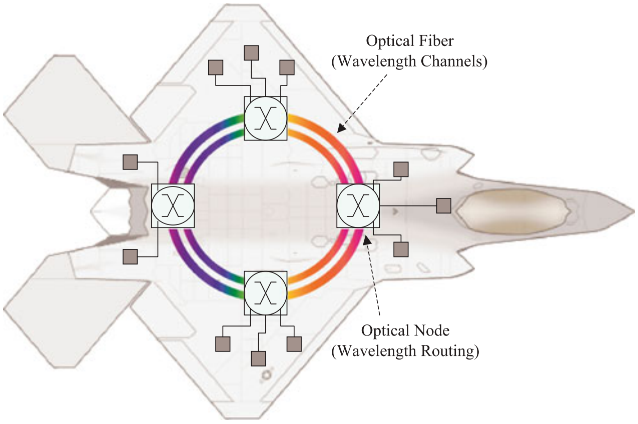

Fig. 6 Aircraft's communication using WDM optical network

In general, UAVs have very constraining operational limits. Designing UAVs is usually limited by weight, speed, endurance time, and power constraints. These constraints limit the amount and size of the UAV's internal systems, their size, weight, and power consumption. In spite of these operational limitations, UAV utilization is significantly growing not only in military applications, but also in other applications such as surveillance and scientific experiments where large amounts of observed data are sensed, processed, and communicated.

Because UAVs are now expanding to cover many applications, they are currently going through more limitations. In particular, many applications (especially in surveillance) have very stringent size limitations. In extreme cases, UAVs that may fly at low altitudes need not be seen by the naked human eye. At the same time, these systems have tasks of collecting (sensing) and processing of massive amounts of data, e.g. high-definition (HD) photographs of locations and

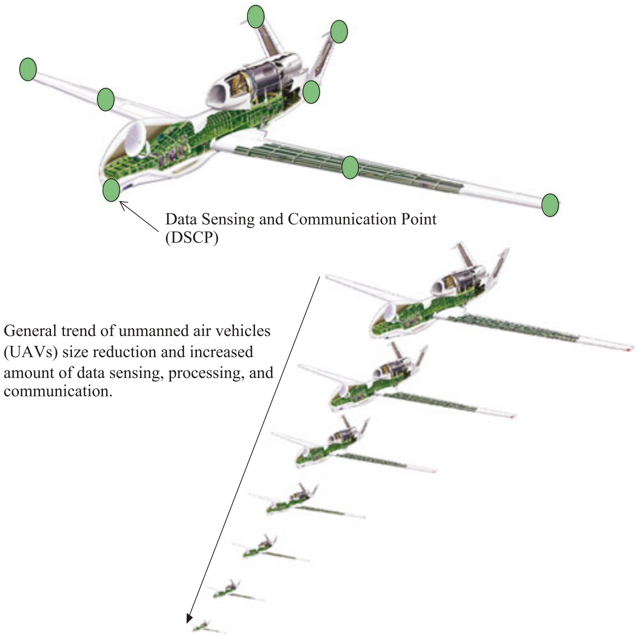

Fig. 7 UAV: general trends in size and communication requirements

targets. As a result, the future UAVs are environed high-scale data communication and processing capabilities (gigabytes or even terabytes), while their sizes are shrinking. This trend is depicted in Fig. 7.

Future UAVs will rely on communication technologies and protocols for various levels of UAV communication: air-to-ground, air-to-air, air-to-user, UAV-to-UAV (inter-UAV), and UAV-subsystem-to-UAV-subsystem (intra-UAV), which require advanced network architectures, in particular mesh networking, interworking with satellites and terrestrial networks, routing and handover, communication techniques for navigation, control, and guidance, and remote autonomous control of UAVs.

We believe that future UAVs with integrated WDM optical networking capability will have substantial benefits for future networking. Our vision is depicted in Fig. 8. In this figure, UAVs with integrated WDM optical networking capability can be used for building 'in-air' WDM mesh optical networks in which a UAV can function as a network hub similar to what is currently deployed in metro and long-haul high-speed optical networks. Such networking capabilities will have astonishing advantages. Specifically, in disaster situations such as earthquakes where ground communication infrastructures are rendered unusable, UAV-based WDM optical networks can provide this communication infrastructure and, most importantly, with similar bandwidth and operational quality.

One important issue that must be carefully analyzed is the reliability of the network. Generally speaking, network reliability is a very critical issue in traditional telecommunication WDM optical networks. The fundamental answer for this issue has always been solved by allocating additional (redundant) resources in the network by using backup nodes and links that are primarily dedicated for network protection. While we can draw on the same concepts on UAV-based WDM optical networks, this new network infrastructure has different limitations. For example, while conventional telecommunication networks deal with unknown (or unforeseen) outage-causing factors such fiber link cuts due to construction operations, in UAV-based WDM optical networks we can have a better estimate of the factors that may cause UAV-based network disruption. A UAV's power usage and endurance information are accurately known. Therefore, UAV-based network outage caused by power issues can be calculated and, therefore, the network architectural design can be more effectively preplanned. Overall, we believe that general limiting constraints that affect UAVs are the fundamental constraints that will continue to affect UAV-based networks.

Overall, using optical networks and WDM technology in avionic systems is based on exploiting the following benefits of WDM optical systems.

- *Transparency*: WDM optical technology is transparent to the data rate as well as to the format of the signal. Therefore, it has the advantage of carrying several systems with different protocols and bandwidth requirements (data rates) that would otherwise require dedicated communication infrastructures.
- *Scalability and flexibility*: WDM optical networks can support a large density of optical wavelengths. New WDM technologies can still utilize the same fiber network infrastructure. Moreover, WDM-based optical architecture also allows for using different set and number of wavelength channels on different links which can be dynamically configured and be customized for different applications.
- *Reliability*: reliability (availability of other communication paths in the case of failure) is a very important aspect. Reliability is achieved by adding redundant paths. In WDM optical networks, this can be achieved by adding light paths which do not impact the physical infrastructure. Also, this allows for multilevel reliability designs in which some communication paths are protected by multiple backup paths.
- *Resources reuse*: a WDM optical network allows for dynamic allocation and reuse of light paths. This allows for efficient management of resources with no additional overhead penalty. For example, two active aircraft subsystems can use the resources of otherwise inactive subsystems.

In spite of the benefits that WDM optical networks bring to mobile systems, integrating these networks into future mobile platforms requires developing new and miniaturized optical networks that can fit in the limiting space of

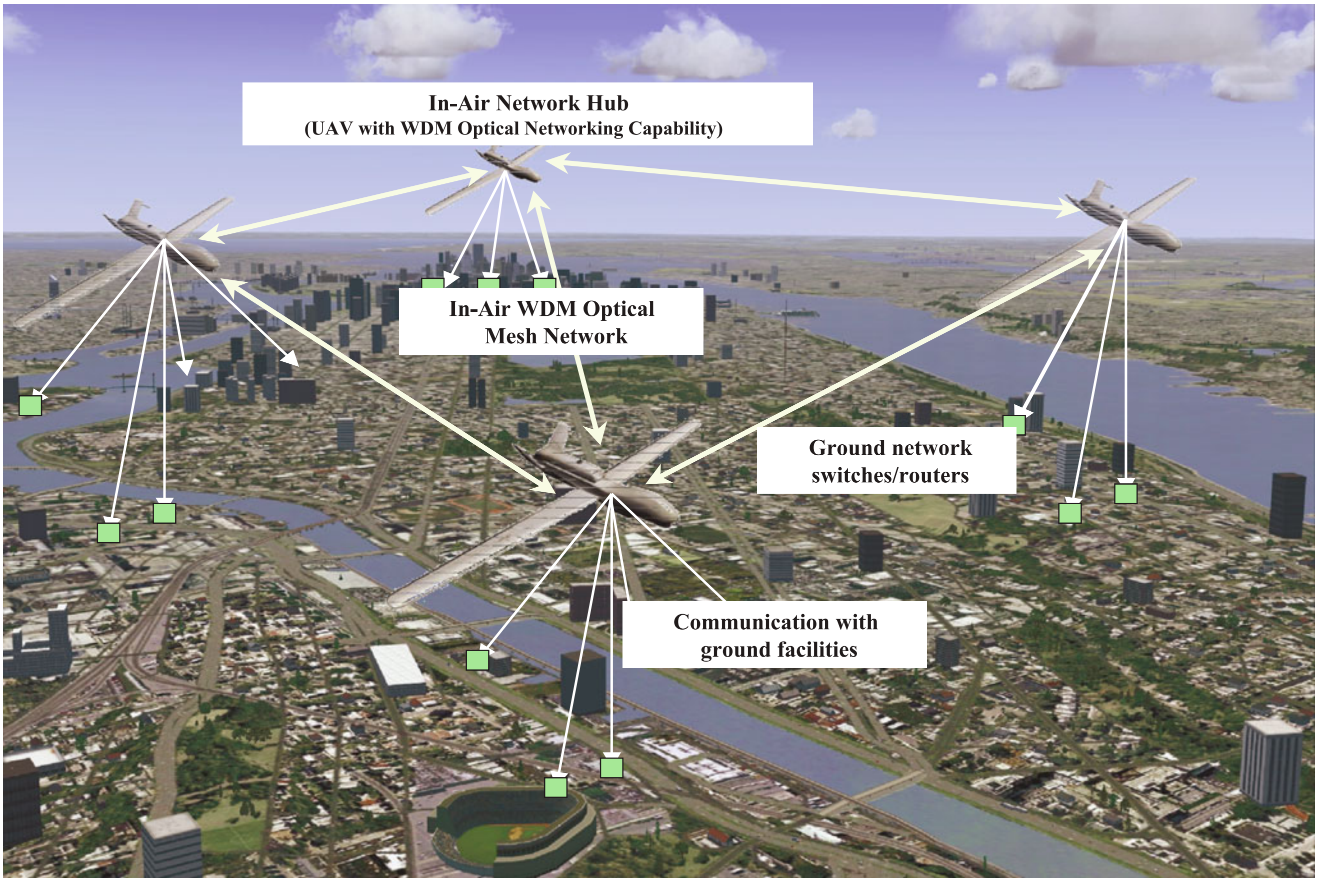

Fig. 8 Future UAV-based WDM optical mesh networks

these systems. The concept of miniaturization seems simple. However, as we reduce the size of optical systems that are typically used in building static networks spanning hundreds or even thousands of miles, integration into mobile platforms like air vehicles requires conducting deep analysis and a comprehensive overview of the potential limitations and hurdles arising from the operating, application-specific, environments.

5 Miniaturization: enabling technologies and limitations

In practice, an optical fiber link can be composed of short sections each having a slightly different core asymmetry. The result of this asymmetry is what is known as birefringence (Fig. 9). Birefringence is the change in the refractive index of the fiber for different polarization states of light. When polarized light (with a state of polarization (SOP) at any given point) travels in the fiber, strong polarization mode coupling variations occur, changing the SOP of the optical signal. Also, slight imperfections in optical fiber design can cause birefringence, which leads some level of distortion in communication. Birefringence in a fiber significantly impacts fiber polarization mode dispersion (PMD). In general, PMD is a limiting factor for high-bit-rate transmission (see [5] for more details).

More important, environmental factors or external stresses such as temperature changes, pressures, stresses, and sudden movements of the hosting system (e.g. aircraft) may cause some stress-induced birefringence (Fig. 9) in the fiber as well as causing random variations in the polarization mode coupling along the fiber link. These random changes in birefringence will affect PMD. As a result, PMD-related effects are also sensitive to a number of environmental constraints. As the size of WDM optical systems shrinks, and since these networks will start to be used in dynamic environments, such physical and environmental effects will be a limiting factor in miniaturization: as the optical networks become miniaturized in size, they become more vulnerable to such effects. Therefore, understanding the dynamics of these effects and their impact on the overall system design is very critical.

In addition, there is a tradeoff between minimizing environmental effects and the corresponding added weight, which is critical for air vehicle systems. Hence, we must determine the optimal point below which (assuming technol-

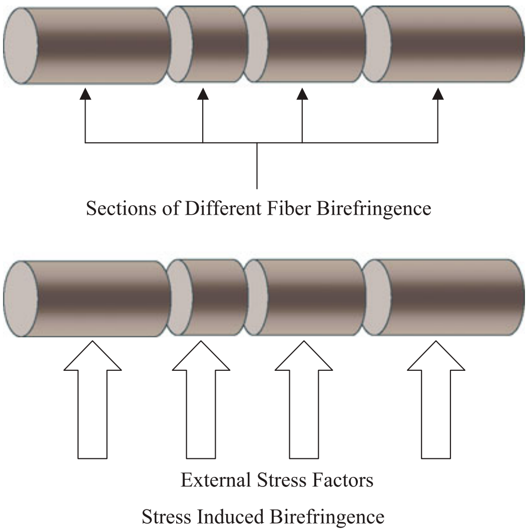

Fig. 9 Stress impact on fiber birefringence

ogy permits) size reduction may not be justified. Note that this is an application-specific question. One of the critical tradeoffs for air vehicle systems is between vehicle weight, energy density of the power source, operational time, and communication capability. This tradeoff will be discussed in more detail in Sect. 7.

In addition to PMD, the design of optical devices has traditionally been limited by the fundamental issue of cross-talk [5, 6]. Cross-talk is an undesirable issue in which an optical signal at a certain input traveling to a certain output is observed at another output. This issue becomes critical at very-small-scale system levels. This is because system components become very close and the level of cross-talk increases. This is particularly a limiting factor in the design of miniaturized optical switches (OXCs).

PMD and cross-talk are among the major hurdles to miniaturization. However, the limitations do not stop at this level. As new technologies are being developed for building future communication and computing systems such as nanotechnology and biotechnology, these technologies have their own limitations.

For example, in making optical components, waveguides [5, 6] are used to guide the propagation of light in the optical device. Waveguides are materials with high index of refraction surrounded by low-index cladding, making the structure capable of guiding the photons. However, miniaturized optical components (used to build miniaturized optical systems) suffer from the scaling limitation of optical waveguides in that bending the light requires high-radius turns. Therefore, nanotechnology in which small waveguides can be created uses photonic crystals. However, the sensitivity of photonic crystals when used in mobile applications under severe stress conditions needs to be better understood.

Also, there has been a vision for miniaturizing current electronic technologies (using CMOS) by developing nanoscale wires. As we know, CMOS is based on two types of transistors: n-type and p-type transistors. It has been very challenging to create n-type nanoscale CMOS transistors. Therefore, the photonic opportunity comes into play in this regard, i.e. it might be possible to combine photonic transmission wires with electronics on a single integrated device that exploits optics as well as electronics.

When it comes to molecular-level communication for developing nanolevel networks, we face a new set of challenges. Molecular communication is based on using massive multiplexing of slowly changing either reactions (molecular multiplexing) or transmission of weak electrical signals in neurons to convey broadband information. Given this dependence on biological systems, the fundamental issue is developing a detailed understanding of molecules and assessing their behaviors in various environments. Several issues arise: controlling the propagation and states of the carrier molecules; encoding and decoding information to extract useful information involving the movements and positions; reactions of cells to initiating and terminating a transmission; and ensuring data integrity in this new medium. One of the key challenges in molecular interconnects is the basic understanding of the physics of the transmission media in order to optimize transmission speed. The biological transmission speed ranging from neuron transmission in axons to the incredibly slow transferring of information in capillaries which operate in a low Reynold's number environment [7] poses interesting challenges. Minuscule improvements in interconnect speed for biological systems can have an extraordinary effect on system performance due to the massive degree of multiplexing involved and it is after all nature's way of communication within biological systems.

6 Hybrid approach: system optimization

As we discussed earlier, miniaturization of optical networks for use in mobile platforms is a broad subject that involves the understanding of other subjects, enabling technologies, and constraints. Therefore, we believe that miniaturization can follow a hybrid approach that exploits the advantages of various technologies for developing interim solutions such as integrating both electronics and photonics on a single chip. This leads us to the discussion of system optimization, i.e. achieving the best system design given certain system parameters and application constraints. If we focus our attention on integrating a WDM optical network on mobile platforms, the parameters are the communication properties of WDM optical networks as well as the capabilities of new technologies. The constraints are the communication constraints of WDM optical networks and the limitations of new technologies.

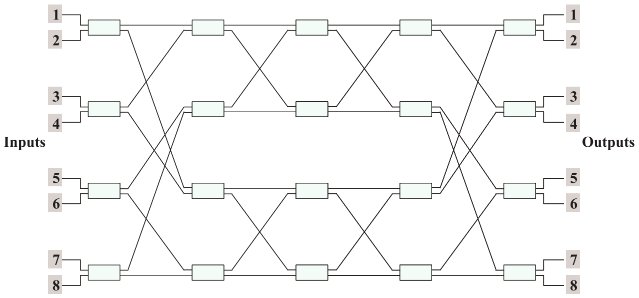

Fig. 10 8 × 8 switch using 20 2 × 2 switching elements (with cross-over)

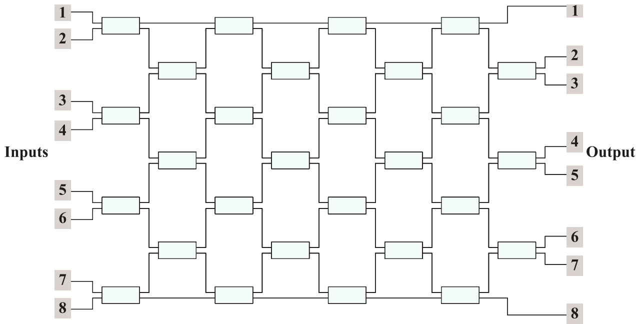

Fig. 11 8 × 8 switch using 28 2 × 2 switching elements (without cross-over)

Considering the miniaturization of optical cross-connects (OXCs), consider the example of building an 8 × 8 optical switch which is built using smaller 2 × 2 switches [8]. We assume the design of a non-blocking OXC: any input port can communicate with any output port at any time as long as the output port is not busy communicating.

A possible way of building the 8 × 8 switch is shown in Fig. 10, which uses 20 2 × 2 switches. The switch design is not planar, i.e. it involves cross-over among some of its links. The number of cross-overs in optical switches is an issue. This is because unlike electronic circuits in which connections between integrated circuit components can be realized at multiple layers, i.e. crossing links do not necessarily physically intersect, in photonics (particularly waveguides)-based architectures, such links have to be made at a single physical layer which leads to physically intersecting the links. If two paths in a waveguide intersect, crossing signals can lose power and cross-talk occurs.

Hence, to achieve acceptable cross-talk performance in an OXC, we must minimize the number of cross-overs. Along these lines, the same 8 × 8 switch can be designed using 28 2 × 2 switches, as shown in Fig. 11. This design has completely eliminated cross-overs. However, it uses eight more 2 × 2 switches. This increases the cost and the power consumption of the solution as well as its weight which will be an issue for either aircraft- or space-based applications. Overall, this is a design-limiting factor for the miniaturization of an OXC.

Given this example, we can see that we have design tradeoffs that must be considered. In this case, and considering a WDM optical network, the overall system design tradeoffs can be combined with the propped WDM optical network communication model (Sect. 3) to achieve various optimization objectives.

7 Miniaturization and communication capacity

The questions we want to ask ourselves are in terms of understanding fundamental limits for the information capacity of systems as we scale the physical volume and how we might be able to overcome limits to the channel capacity of a single communication channel. First, we start with the fundamentals based on Shannon's theory of communications [9], which determines the ultimate capacity of a communication channel having additive Gaussian white noise (AGWN)

$$C = B \times \log_2(1 + \mathrm{SNR}), \tag{21}$$

where C: channel capacity (bits/s); B: channel bandwidth (Hz); SNR: signal-to-noise ratio = P_s/N, where P_s is the signal power and N is the noise power in the bandwidth B. The noise power can also be expressed as $N = N_0 \times B$, where N_0 is the noise spectral energy density.

An illustrative example is for $P_\mathrm{s}/N \ll 1$ and Shannon's expression reduces to $C = 1.44(E_\mathrm{s} \times R_\mathrm{p})/N_0$, E_s is the signal energy and R_p is the repetition bit rate. In the thermal noise limit, $N_0 \sim kT$, where k is the Boltzmann constant and T is the temperature in K. Thus,

$$C \sim 1.44 \times \left(\frac{P_\mathrm{s}}{kT}\right) = \frac{E_\mathrm{B} \times R_\mathrm{p}}{kT}, \tag{22}$$

where E_B is the energy per bit; for bit error rates $\ll 10^{-7}$, P_s/kT needs to be ≥ 10 (we will assume that $P_\mathrm{s}/kT = 10$).

The total energy available to a mobile system, E_T, is given by

$$E_\mathrm{T} = E_\mathrm{D} \times m, \tag{23}$$

where E_D is the energy density of the energy supply in W h/kg and m is the mass of the energy source.

For an advanced Li ion polymer battery, the energy density is ~100 W h/kg and thus for a 1-kg mass we get $E_\mathrm{T} \sim 100$ W h, which corresponds to 3.6×10^5 W s.

What would be the ultimate capacity, C_U, of such a system?

The operational communication time, T_O, for a mobile system is given by $T_\mathrm{O} = E_\mathrm{T}/P_\mathrm{s}$. We have the following relationship for mobile systems, where we have assumed that

$C_\mathrm{U} = R_\mathrm{p}$.

$$T_\mathrm{O} \sim 0.1 \times \frac{E_\mathrm{T}}{kT \times C_\mathrm{U}}. \tag{24}$$

In addition, the product of operational time, T_O, and information capacity, C_U, is given by

$$T_\mathrm{O} \times C_\mathrm{U} = 1.44 \times \left(\frac{E_\mathrm{T}}{kT}\right). \tag{25}$$

Calculating C_U for a one hour of operation time and a temperature of 300 K, we get

$$C_\mathrm{U} \sim 3.5E^{21}\,\mathrm{bits/s}. \tag{26}$$

In (26), we have assumed that the entire power system is funneled into communications, which is clearly unrealistic. A more reasonable assumption is to assume only 5% of the energy going into communications (most of the energy goes into keeping the mobile system in the air, and this is especially the case for the low Reynolds's numbers regime). In addition, we have also assumed a transmission distance of zero and no other link losses for RF transmission. If we take a nominal communication distance of 1 km, and assume that the transmitter is a point source with $(1/R^2)$ free-space loss (R is the distance from transmitter to receiver), 10 dB of additional losses and amplifier noise (noise figure), and 20% electronics efficiency, we get a more reasonable, but significant, C_U for a 1-km transmission distance and an operational time of 1 h for a vehicle having a 1-kg Li-ion battery source:

$$C_\mathrm{U} \sim 0.7\,\mathrm{Gbps} \tag{27}$$

at a 1-GHz operating carrier frequency.

The key message is that small mobile systems can have significant information capacity, but it scales with the mass of the energy source (and thus the mass of the vehicle). However, as we shrink the volume of the mobile system to 1 g or less, the maximum capacity drops beyond three orders of magnitude.

The ultimate capacity, C_M, is limited by quantum effects, the uncertainty principle, and thermal noise and is given by [9]

$$C_M = \left(\frac{2 \times E_1}{h}\right) \times M, \tag{28}$$

where E_1 is the minimum energy for generating a bit, h is Planck's constant (6.62E^{-34} J s), and M is the number of quantization levels; thermal noise energy is $\sim kT$ and thus E_1 can be no less than kT, where k is the Boltzmann constant (1.38E^{-23} J/K).

The lower bound for C_M at room temperature and $M = 1$ (binary system) is

$$C_M \sim 12\,\mathrm{Tbps}. \tag{29}$$

The key message for small systems is that due to the energy constraints resulting from the small volume, the channel capacity and operational time are inherently linked and result in an operational time-maximum capacity product which is proportional to energy density divided by operating temperature. As we try to increase the channel capacity, the operational time for the mobile system rapidly decreases and, if we want a long operational time, then we need to increase the mass of the energy source, increase the energy density of the power source, decrease the operating temperature, or decrease the channel capacity. New discoveries in providing more energy from smaller systems (e.g. using either higher density battery technology or other novel sources of higher energy density) could alter the constraints. Fundamentally, for small systems to have large information capacities (and also long operational times) comparable to larger systems, either the noise sources need to be below the fundamental (kT) limit or significantly larger energy density sources would be required. With the currently known physics, we do not know how to accomplish this. In the thermal noise limit, the capacity (from (22)) can be increased by lowering the temperature without impacting the operational time. From a classical perspective, this would allow arbitrarily low signal powers to achieve a given capacity as we lower the temperature. However, current methods for lowering the temperature cost energy and would also drain the finite energy source, and thus require a larger mass. It would seem that we would violate the second law of thermodynamics if we are able to lower the temperature of a system without incurring any energy dissipation. One method for increasing total system capacity in a channel with limited channel capacity it to use massive multiplexing (for example using spatial multiplexing) of individual channels so that even though each channel carries a limited amount of information, the aggregate can carry extraordinary amounts. In the case of miniaturized autonomous vehicles, this implies that while each autonomous vehicle will have limited information capacity, the aggregate system capacity of a swarm of autonomous vehicles can be significant. Another method for increasing the capacity of a mobile system is to use a large mesh network where each node behaves as a repeater and thus the distance between nodes can be significantly reduced with a corresponding reduction in free-space loss and an increase in capacity (assuming that we can figure out how to improve the efficiency). The human body serves as the classic example of a system using multiple methods of multiplexing, and a mesh network for increasing total system capacity to perform functions of enormous complexity such as vision and problem solving.

In addition, the vision of miniaturized optical networks on small mobile systems that can be used for building futuristic network architectures that are very integrated and dynamic is fueled by various research efforts [10–21] that provide concepts and solutions which may be effective for this future vision. Nevertheless, we believe that this a long-term research problem spanning various fields and, thus, requires following a multidisciplinary approach ranging from fiber-optic physics to opto-electronics to optical switching to network architectures and protocols to algorithms to mathematical optimization. It also requires understanding the limitations of the operating environments and their requirements [22–29].

8 Conclusion

In summary, the exponential growth of data communications including the emergence of new applications is becoming more network centric. The current electronic technocrats cannot sustain this massive growth and new technologies must be devised to meet such ever-increasing demands. The vision is integrating WDM optical networks in mobile systems such as unmanned air vehicles (UAVs) and we explained the benefits of WDM optical technology for such applications. We also studied the operation limits for these applications and, hence, we described some of the limitations of WDM optical miniaturization for ultra-small platforms. We investigated the advances in WDM optical technology and their general applications for data communication and networking. We studied the communication constraints in WDM optical networks and presented a mathematical optimization model that reflects various parameters in WDM optical network design and signal routing. This model can be used as the basis for performing system-level optimization when optical networks are integrated into new environments (e.g. UAVs) that introduce additional sets of constraints. We investigated the vision of integrated miniaturized WDM optical systems for use in mobile platforms. We studied several enabling technologies and developments such as nanotechnology and investigated their limitations. Overall, we believe that there exist tremendous opportunities for miniaturized WDM optical technology which is fueled by the miniaturization-enabling technologies. However, this is a multidisciplinary field which requires the cross-dissemination of ideas and solutions from other areas and is a long-term research problem.

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