Strategies for resource provisioning in optical networks supporting broadband wireless access networks

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We investigate the provisioning of optical-frequency (wavelength) resources in optical networks that support broadband wireless access networks (BWANs). Millimeter-wave–over–fiber technology with operation in the 60-GHz license-free band is considered for the BWANs. The WDM-based optical network (handling BWAN traffic) is heterogenous, implying that it also bears traffic originating from (or destined for) wireline terminals. A discrete-event simulation is devised to ascertain the minimum number of wavelength channels required for various cases. Three WDM transmission schemes (pure, semihybrid, and hybrid) are described and used in the simulations. Hybrid WDM was observed to require the least number of wavelengths. However, the easily implementable pure-WDM scheme could be considered even if only a limited number of wavelength converters were deployed in the network. © 2003 Optical Society of America

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1. Introduction

Telecommunications service requirements are currently evolving into ultrabroadband ($\gg$2 Mbit/s) services such as high-quality streaming video, Gigabit Ethernet (GbE) leased lines, and pay-per-use software. The revenue-generating potential of these services coupled with the deregulation of the telecommunications market has attracted new entrants into the telecommunications sector and has intensified the competition. In such an environment, high demand exists for innovative network designs that offer cost-effective, flexible, and tetherless platforms. These platforms create the possibility of supporting a diverse services portfolio, thus ensuring maximum returns on network investments.

The metropolitan and access (the so-called last or first mile) parts of the telecommunications network hierarchy remain relatively underdeveloped compared with high-capacity backbone networks and thus create an ultrabroadband bandwidth "bottleneck" as far the end-user is concerned [1]. The considerable fiber cabling costs and low levels of equipment sharing (especially in least densely populated areas) make the deployment of fully end-to-end fiber-optic networks impractical. Therefore the final part of the network has to rely on an array of networking technologies that maximize the utilization of the existing legacy infrastructure [e.g., digital subscriber lines, cable modems, VSATs (very small aperture terminals)] to support the demand for broadband services [2].

Of the emerging networking technologies, broadband wireless access networks (BWANs) are proving particularly attractive in an unbundled (deregulated) access network environment. The BWAN enables new entrants to provide broadband services without the need to rent legacy infrastructure from the incumbent operator. Moreover, network operators can mitigate investment risks by deploying end-user equipment only when demand arises. The millimeter-wave (MMW) band, in particular the one located at the oxygen absorption band (60 GHz), presents opportunities for wireless data rates of over 100 Mbit/s. Furthermore, this band is being explored as an outdoor extension of the increasingly popular wireless local-area networks (WLANs) [3]. The high data rates supported by MMW-band communication systems have meant that only fiber optics can provide the sufficient bandwidth and transmission range for the interconnection of the central station, base stations, and/or MMW antennas [4]. Moreover, this MMW-over-fiber system enables the centralization of most system functions thus enabling compact (cheap) base station designs, and it simplifies network upgrade procedures [5]. The general architecture of such a MMW-over-fiber system is shown in Fig. 1.

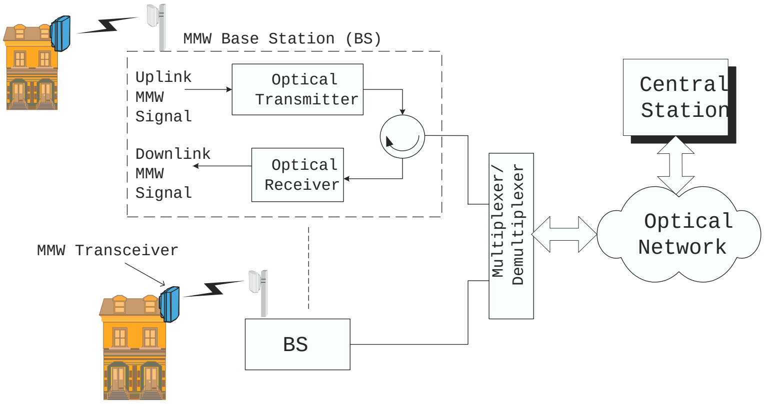


Fig. 1. General MMW-over-fiber system.

It is expected that the large-scale deployment of BWANs should have a significant effect on the traffic engineering of the bearer optical-based access and metropolitan networks. Wavelength-division multiplexing (WDM) is expected to be the dominant transmission scheme for the optical layer [1]. When WDM is used, the semipermanent connections in a network are dynamically set up and torn down by assignment of wavelength(s) to connections on predetermined routes. In practice, owing to the physical limitation of optical devices and fiber waveguides, only a finite number of wavelengths can be utilized in a WDM network [6]. As a result, some requests for network connections might be rejected if all the available wavelength channels are occupied at a particular instance. Therefore the scarcity of wavelengths implies that the methodologies of provisioning wavelength channels should also take into account the BWAN capacity demand and architectures. Our primary objective in this study is to investigate various ways of accommodating MMW-based BWANs on existing optical networks with the minimum of strain on the available wavelength resources.

The remainder of this article is organized as follows. Section 2 reviews the architecture of the various hierarchies of the network. The methodologies for allocation of wavelength resources are discussed in Section 3. In Section 4 wavelength requirements are simulated, and the results are discussed further in Section 5.

2. Overall Network Architecture

Traditionally, the tiers of a hierarchical telecommunication network are arranged according to geographical coverage. As networking technologies evolve and with the telecommunications market in a constant state of flux owing to deregulation, the traditional boundaries between the tiers have become increasingly blurred. This is best illustrated by, for instance, the adoption of Ethernet (a prominent LAN technology) for access, metropolitan, or even backbone networks [7]. This study focuses on a *metropolitan access network* (MAN) similar to that discussed by Saleh and Simmons [1]. For the sake of generality, we adapt a tripartite partitioning of the tiers into feeder, distribution, and customer networks (Fig. 2). Since the level of traffic aggregation in feeder and distribution networks is earmarked to be in the multigigabit-per-second range, then optical fibers are the only viable transmission medium.

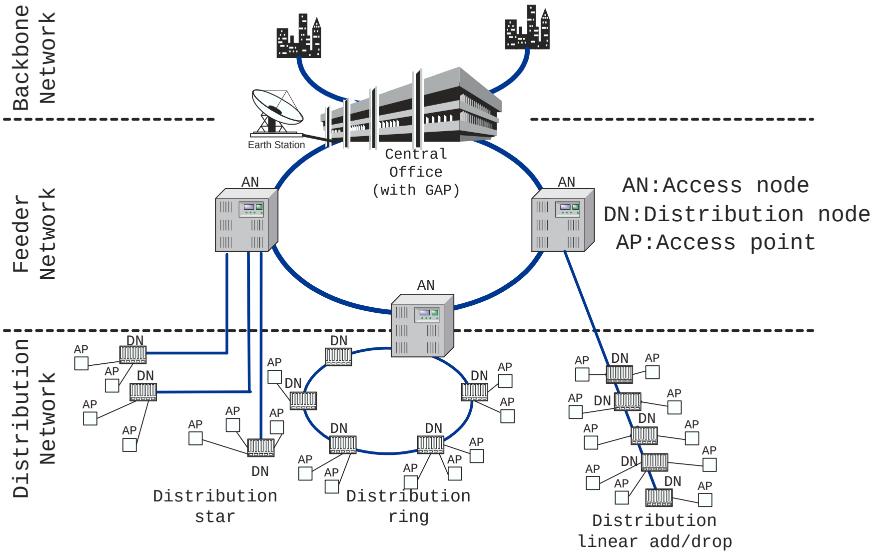


Fig. 2. Hierarchical metropolitan access network.

2.A. Intelligent Feeder Networks

The fiber-optic feeder network interconnects various access networks in a metropolitan region with a diameter of 10–100 km. Each primary service area of the metropolitan region is allocated an optical access node (AN) that enables wavelength channels bearing traffic (audio, visual, data) to be dropped to (or added from) the service area. For enhanced flexibility, ANs can be reconfigured to drop or add certain channels by means of changing switch configurations and/or using wavelength converters (WCs). Various optical technologies [e.g., MEMS (microelectromechanical system), Bragg gratings, InP devices] have been proposed for implementing ANs [8]. A gateway AN (GAN) is a special AN equipped to hand over traffic to the backbone network, neighboring MANs, or landing points for undersea fiber networks. In practice the (G)ANs could also be conveniently co-located with other service-provider facilities such as cable headends, servers for an Internet service provider's POP (point of presence), or telephone exchanges.

The feeder networks are usually implemented with robust two- or four-fiber WDM shared protection ring (SPRING) configurations [6,9]. In both configurations, service restoration is done by means of looping back the traffic away from a failed link or node over spare fibers running in the opposite direction. A feeder network may have different parts of its infrastructure provided by different vendors and support internetworking between different carriers. Standardization is therefore necessary to ease interworking between various network elements and carriers. This should enhance the intelligence (signaling and routing functions) of the nodes, which in turn allows dynamic service provision and restoration. To that end the standardization of the optical-layer control plane (OCP) over the optical layer is being carried out by various bodies. Most notably, the International Telecommunications Union (ITU), Internet Engineering Task Force (IETF), and Optical Internetworking Forum (OIF) have developed standards for the automatic switched optical network (ASON), generalized multiprotocol label switching (GMPLS), and user–network/network–network interfaces (UNI/NNI), respectively (see Ref. [10] and references therein).

2.B. Distribution Network

The optical distribution network provides connectivity between the feeder network and the user equipment or customer premises networks (CPNs). The fiber cables in distribution networks could be deployed in linear, tree, ring, or star topologies (see Fig. 2) depending on the service area's demography, survivability requirements, and other cost considerations. Distribution nodes (DNs) are used in these networks analogous to ANs in the feeder network. However, since the level of sharing of the distribution network infrastructure is lower than in the feeder network, then the cost of DNs (hence complexity) has to be lower than with ANs. Two implementation possibilities exist, reconfigurable DNs or the cheaper fixed DNs. In the latter case, the wavelength channels that could be added from (or dropped to) an end user are fixed, thus reducing the flexibility and wavelength reuse.

The capacity or subscriber base of the distribution network can scaled by means of deploying extra DNs or increasing dimensions of existing DNs. From a conceptual point view, the ADD and DROP ports of the DNs are linked to terminals or access points (APs) via a user–network interface. Typically, at an AP a downstream optical signal is converted into an electrical signal and down-converted to a frequency suitable for transmission over a particular media type (e.g., coaxial cables, air). A reverse process is carried out for upstream signals. If the subsequent medium is air, the fibers are terminated at a radio-access point (RAP); otherwise they are terminated at a fixed-access point (FAP). The wireless antennas at a RAP can be deployed in either point-to-point, point-to-multipoint, or meshed configurations as shown in Fig. 3. In the latter two configurations, RAPs are shared by multiple users and non–line-of-sight (NLOS) links are feasible [11].

2.C. Broadband Wireless Access Technologies

The high levels of penetration of the second-generation (2G) cellular network services [e.g., GSM (global system for Mobile communications), IS-54, PDC (personal digital cellular)] has firmly established the presence and popularity of wireless networks. Current efforts are geared towards upgrading these networks to support multimedia services according to the 2.5G [GPRS (general packet radio service), EDGE (enhanced data rates for GSM evolution), iMode, and 3GSM (third-generation GSM services)] and 3G [UMTS/IMT-2000 (universal mobile telecommunications system/international mobile telecommunications–2000)] standards with data rates peaking at 2 Mbit/s [12]. Unfortunately, this still falls short of the rates attainable over current widespread wireline access network solutions such as cable modems (10 Mbit/s). This has increased the support for public WLAN technologies are seen as a competitive broadband service platform for the subsequent (4G) generation of wireless networks [13,14]. With the delayed transition to 3G, suggestions are emerging that WLANs may disrupt the smooth 2.5G to 3G to 4G evolution envisioned earlier [15].

Current WLANs have variable specifications but are generally based on standards prepared by three major bodies: the Institute for Electrical and Electronics Engineers (IEEE),

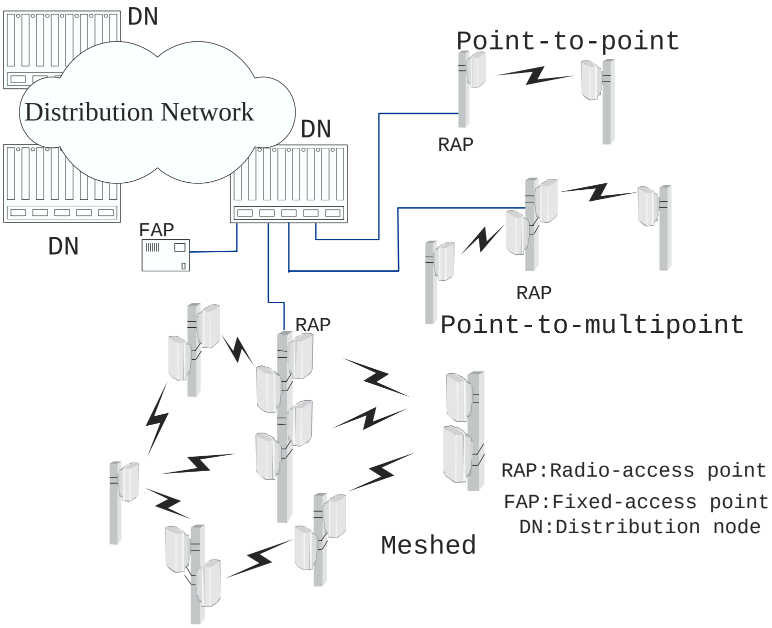


Fig. 3. Terminals connected to a distribution node (DN) and various fixed-wireless topologies.

the European Telecommunications Standardization Institute (ETSI), and the MMAC (Multimedia Mobile Access Consortium) [12]. The highest data rates (up to 54 Mbit/s) standardized by the three bodies employ the Unlicensed National Information Infrastructure (5-GHz) band and are known as IEEE 802.11a, ETSI broadband radio access networks (BRAN) HIPERLAN Type 2, and Association of Radio Industries and Business (ARIB) MMAC HiSWAN, respectively. Notably, the 54-Mbit/s peak rate is achieved only by stationary or pedestrian paced ($\leq$ 1.5 m/s) mobile terminals in indoor environments. The high-speed WLAN could be bridged to the wireline feeder/distribution network via a fixed wireless access network operating in the MMW radio band [3,16]. The license-free 60-GHz band (oxygen absorption band) has already been identified for this purpose, and its contiguous 5-GHz bandwidth should support some very competitive data rates ($>$100 Mbit/s) for distances up to 2 km [14]. Active 60-GHz standardization efforts include the MMAC standards for an ATM-based WLAN and IEEE 1394 high-speed links with data rates of up to 156 and 100 Mbit/s, respectively [17]. The IEEE has also developed standards (IEEE 802.16) for fixed BWANs that fall within 10–66-GHz frequency range [17]. In Europe, among the leading 60-GHz band initiatives is the MEDIAN project [Advanced Communications Technologies Services (ACTS) AC 006], which has carried out demonstrations for WLANs and wireless CPNs with rates of up to 150 Mbit/s [18].

2.D. *Technology Convergence*

The interworking (system handover) between the 5- and 60-GHz bands is one of the most crucial features of 4G systems. This opens up the possibility of using 60-GHz-band WLANs for indoor environments (as well as 5-GHz-band WLANs for outdoor applications) with multiband user terminals [3]. The 60-GHz band has severe path loss (10–15 dB/km) and stringent line-of-sight (LOS) requirements that present a formidable design challenge for indoor environments that usually contain many obstructive objects (e.g., furniture, people) [3]. Further improvements (with negligible increases in cost per transmitted bit) in the design of 60-GHz systems should ease that convergence. Among the solutions being proposed is the use of orthogonal frequency-division multiplexing (OFDM) [16], innovative antenna designs [13], and software-defined radio techniques [13].

The increasing use of the Internet implies that the traffic of future networks will almost certainly be IP dominated. Such dominance guarantees a *de facto* evolution of current voice-optimized networks toward IP-centric future converged networks dominated by data traffic. For instance, the third and subsequent generations of wireless networks will constitute various systems (e.g., WLAN, cellular, satellite) operating on a common IP platform with seamless intersystem handover capabilities [13]. The convergence of physical-layer technologies is also necessary to simplify the interface between optical and wireless networks. This requirement is reflected in the developing synergy between rf and optical-domain device technologies [19].

3. Resource Provisioning

Traffic engineering (TE) embodies the techniques for improving network resource utilization ability to meet traffic demand so as to boost network efficiency and robustness. A WDM-based optical network (wavelength-routed network) achieves TE by using *routing and wavelength assignment* (RWA) algorithms to identify a suitable route for the connection and to allocate wavelength channels [20]. Typically, the network connection management system monitors all the admissable routes and arranges them into a path list in order of ascending or descending hop length and/or load. In turn, those parameters are used as the selection criteria of the RWA algorithms. In a heterogenous MAN that supports MMW systems, several WDM schemes could be implemented to enable the APs to share the optical capacity.

However, only a limited number M of distinct wavelengths labeled $\{\lambda_1, \lambda_2, \ldots, \lambda_M\}$ can be utilized in a WDM network, owing to the narrow optical amplification bandwidths, fiber nonlinearities, and low wavelength selectivity of optical devices [6]. In the likely event that no wavelength channels are free when a connection request arrives, the request is rejected and the connection is said to be *blocked*. The adverse consequences of blocking include loss of revenue, reduced competitiveness, and service dissatisfaction. Wavelength converters (preferably all-optical) can be used to reduce blocking by relaxing of the wavelength-continuity constraint on the RWA algorithms [21].

3.A. *Possible Methodologies*

Various techniques have been proposed to increase the number of usable wavelength channels. The most explored option has been to increase the transmission window (e.g., by the use of wideband fibers or amplifiers) or reduce the channel spacing with more precise or selective components. Unfortunately, these techniques may require "fork-lift" upgrades of existing and higher component-fabrication costs. An alternative technique would be to increase the efficiency of reuse of the existing wavelength channels (in addition to possible use of WCs). To that end, optical packet switching is being developed to provide statistical multiplexing gain in the optical layer, though the necessary enabling technologies have yet to mature [22]. In this article we focus on the techniques based on the use of an extra degree of freedom (in addition to the wavelength) to reference a channel by employing other distinguishing properties (e.g., time, space, signal polarization, codes, subcarriers) of the signal stream. The result is an xDM/WDM transmission, whereby WDM is hybridized with a multiplexing method employing a distinguishing property x. Therefore the NxDM channels labeled $\{x_1, x_2, \ldots, x_N\}$ share a single wavelength, guaranteeing up to $M \times N$ channels in the network. In this case the channel is labeled as $x_i\lambda_j$. In the remainder of the article, RWA will denote routing and channel assignment (RCA) so as to account for assignment of $x_i\lambda_j$ dual-labeled channels.

In this study, we consider three WDM schemes depicted in Fig. 4 and described briefly below.

(a) *Pure WDM*: each AP (FAP or RAP) is assigned at least one single dedicated wavelength for a connection. Occasionally, a single AP may demand more than a single wavelength—owing to increased capacity demands—needed to support multiple electronic service types (e.g., IP, frame relay) or use of antenna arrays [23].

(b) *Semihybrid WDM*: up to N signal streams from multiple RAPs sharing a DN are x-division-multiplexed to share a single wavelength channel.

(c) *Hybrid WDM*: up to N signal streams from both multiple RAPs and FAPs are x-division-multiplexed to share a single wavelength channel.

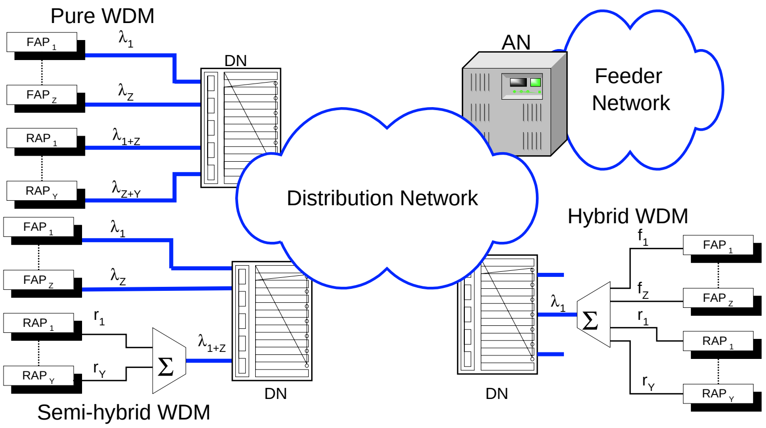


Fig. 4. Various WDM schemes considered in the study of the heterogeneous networks. Each DN supports Z and Y FAPs and RAPs, respectively. The number of wavelengths required above for the pure, semihybrid, and hybrid WDM schemes is $Z+Y$, $1+Z$, and 1, respectively.

It must be noted that the optical-frequency grid of MMW-over-fiber signals (to and from RAPs) differs from that of baseband signals (to and from RAPs). In the latter case, signals occupy a single slot on the frequency grid with a spacing of f_Δ compatible with ITU grid specifications. By contrast, the former signals will also have two sidebands f_M on either side of carrier, where f_M is the carrier frequency of the MMW signal. However, MMW signal fading usually occurs at the RAPs signal, owing to the fiber-dispersion-induced phase-mismatched beating between the two sidebands. This creates the need to suppress either one of the sidebands or the carrier [24]. Therefore each MMW-over-fiber signal would—in most cases—occupy two slots on the optical-frequency grid. This fact has to be taken into account in designing WDM components and wavelength planning for heterogenous networks. Moreover, connections between FAPs and RAPs will need to go through interface devices to enable signal reception at either AP. A straightforward design measure could be to enforce a $f_\Delta - f_M < f_{\min\Delta}$ constraint, where $f_{\min\Delta}$ is least possible optical-frequency spacing. This places unacceptable upper limits on the optical spectral efficiency. We can eliminate this constraint by performing intricate optical-frequency interleaving of the mixed signal types or using wavelength banding to maintain different signal types in separate bands.

3.B. Comparison of xDM/WDM Hybrids

In semihybrid and hybrid *x*DM/WDM schemes, the *x*DM is used to combine signals prior to modulating a common optical source so as to share a single wavelength channel. Several multiplexing techniques have been proposed for optical systems, the most notable being electrical time-division multiplexing (ETDM), subcarrier multiplexing (SCM), optical time-division multiplexing (OTDM), optical code-division multiplexing (OCDM), and polarization-division multiplexing (PDM). The advantages and respective limitations of implementing those techniques are listed in Table 1. In most active optical networks, signals are multiplexed electrically before the WDM stage, with one of the widespread voice-centric ETDM standards such as PDH or its successor, SDH/SONET (synchronous digital hierarchy and synchronous optical network) [6]. Another popular electrical multiplexing scheme is subcarrier multiplexing, whereby multiple electrical signals are multiplexed in the rf domain and then modulate a single optical source [25]. Baseband signals and MMW carrier aggregation could also be considered to be in this category [26]. SCM has been a longstanding solution for distribution of analog video signals over the CATV network. Moreover, SCM/WDM MMW-over-fiber systems have been demonstrated in laboratories [27].

Table 1. Advantages and Limitations of Various Multiplexing Methods

*x*DM	Advantages	Limitations
ETDM	-Mature, widely deployed -Electronic packet switching available	-Complexity increases rapidly with wavelength number -Electronic bandwidth “bottle-neck” -Inflexible, format dependent
SCM	-Cheap, mature microwave technologies -Dispersion tolerant optical SSB implementable	-Bandwidth limited by modulation frequency of optical transmitter -Highest subcarrier frequency limited by fiber dispersion
OTDM	-Ultrafast line rates ($>$100 Gbit/s)	-High fiber-dispersion penalties -Immature technologies -Timing synchronization required -Still expensive
OCDM	-Soft capacity -Increased security -No need for synchronization	-Bipolar optical coding difficult -Severe dispersion (for temporal codes) -Adding–dropping coded signals difficult
PDM	-Tolerance to polarization-mode dispersion	-Variable polarization on fiber causing polarization cross talk -Complex demultiplexing -Polarization-dependent losses

The other optical-layer multiplexing techniques have been implemented only in laboratories and in various field trials. In the OTDM technique, all-optical interleaving is used to aggregate multiple lower-rate optical signals. Hybridization of OTDM with WDM record-breaking multiterabit-per-second "hero" transmission experiments (bandwidth efficiency ≥ 1 bit/s/Hz) has been possible [28]. The target for such trials is for possible implementation in future long-haul (hundreds of kilometers) links. PDM/WDM hybrids are also being developed to perform similar roles [29]. On the other hand, the focus on hybrid OCDM/WDM has been mainly on networks with significantly shorter link distances [30]. A more detailed study of the suitability of each multiplexing technique for semihybrid and hybrid WDM MMW systems is beyond the scope of this paper.

4. Performance Analysis

Here we define the following:

- $AN_{\max}$: Number of ANs (including GAN) deployed in the feeder network.
- $DN_{\max}$: Maximum number of DNs that could be deployed in a distribution network.
- $AP_{\max}$: Maximum number of APs that could be connected to a DN.
- $D = (d_{ij})$: $DN_{\max} \times AN_{\max}$ matrix whereby $d_{ij} = 1$ if the ith DN using the jth AN is active $d_{ij} = 0$ otherwise (inactivity also signifies nonexistent component).
- $A = \left(a_{ij}^{k}\right)$: $DN_{\max} \times AN_{\max} \times AP_{\max}$ matrix whereby $a_{ij}^{k} = 1$ if *the* kth AP at the ith DN using the jth AN is an RAP active, $a_{ij}^{k} = 2$ if kth AP at the ith DN using the jth AN is an FAP active, $a_{ij}^{k} = 0$ otherwise.
- $a_{ij}^{k} \leftrightarrows a_{lm}^{n}$: Connection between a_{ij}^{k} and a_{lm}^{n}.

4.A. Problem Description

The problem outlined here is for an offline RCA, whereby all the undirected lightpaths are known in advance. The routes are predetermined by use of fixed shortest-hop-number routing, because power penalties (hence signal impairment) attributed to nodes are more prominent in MANs that tend to have relatively shorter internodal distance. For the BWAN case, the ANs and GAN are assumed also to perform the role of control stations and a central control station, respectively. Therefore, for the connection

$$a_{ij}^{k} \leftrightarrows a_{ij}^{n}, \qquad k \neq n, \forall ij,$$

the lightpath will be confined within the distribution network. In this case, all members of A and D are assumed to be fully reconfigurable. The problem of assigning channels interconnecting terminals in the electrical domain (which involves logical topology design and grooming problems) has been studied extensively [20] and thus will not be considered here. A maximum load dimensioning model is used to ascertain the minimum number of distinct wavelengths required (λ_R) for a given set of active and new connections. The load L in this case refers to the maximum of number of lightpaths carried on any link. For an α-fiber ring topology $\lambda_R = \lceil \frac{\alpha+1}{\alpha} L - 1 \rceil$, where $\lceil q \rceil$ rounds q toward ∞ (Ref. [31]). Moreover, for star and bus topologies with k-fiber links (k is even) $\lambda_R = \lceil L/k \rceil$. The introduction of WCs with full conversion capabilities means that $\lambda_R = L$ for all topologies.

All the channels are arranged in a channel list according to, for instance, label number (ordering for online RCA is according to usage). In this case the ith connection requiring $\lambda_{Ri}\,(\leq 1)$ channels is assigned a similar number of free channels beginning with the lowest labeled channel. These channels could be in use (i.e., they are active) elsewhere except for the route assigned to the lightpath. If none of the active channels are free for that particular route, then an inactive channel is assigned from the list and λ_R is incremented. For the pure WDM case, the list is a one-dimensional λ_i list and λ_R is incremented by λ_{Ri} if no free active channels are available. In contrast, the semihybrid and hybrid WDM cases have a channel list that is a two-dimensional $x_i\lambda_j$ list, and the λ_R increment is $\lceil \lambda_{Ri}/N \rceil$. However, for the former case, if

$$a_{ij}^{k} \leftrightarrows a_{lm}^{n}, \qquad a_{ij}^{k} \neq 1, \forall ijlm,$$

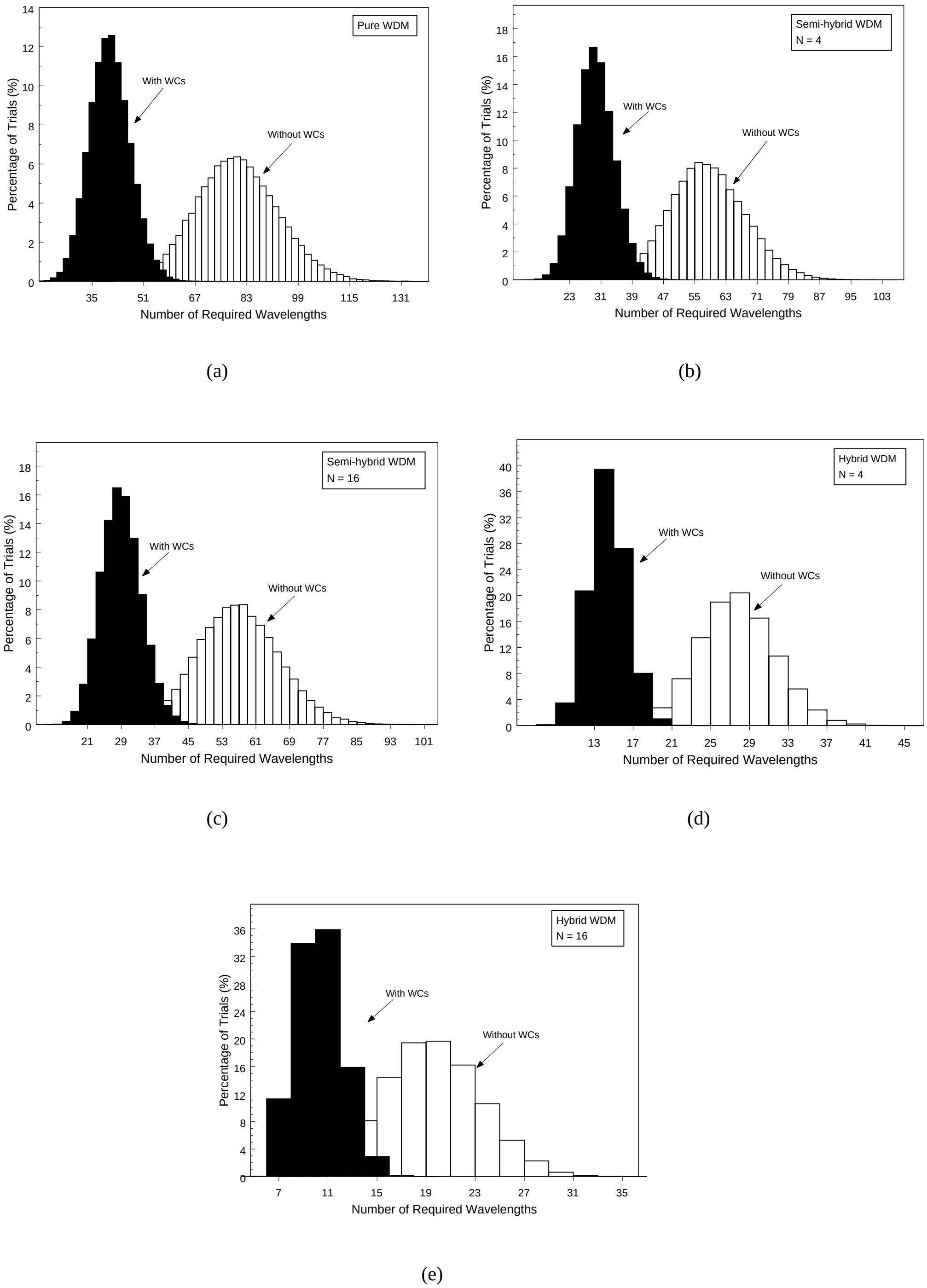
then the channel list could be perceived to be a one-dimensional λ_i list.

4.B. Simulation Results

The MAN of Fig. 2 with $AN_{\max} = 4$ and depicting three types of distributed network topology was employed as the study case. A discrete-event simulation routine is devised whereby an event is the addition or deletion of DNs or APs. For each simulation run (trial), the number of DNs and APs is varied randomly with $DN_{\max} = 10$ and $AP_{\max} = 14$. Therefore the number of demanded connections is also refreshed after each trial by generation of a new set of connections according to Poisson statistics. Network utilization of less than 100% is assumed throughout. The variations described above ensure that observations are made from as many diverse topological and demand situations as possible. This should mirror a highly competitive telecommunications market, whereby the influx and churn of customers occurs more regularly. Several additional assumptions were made in the simulations, as follows:

- A four-fiber WDM SPRING is used for the feeder network.
- There is symmetrical traffic demand between any arbitrary AP pair.
- There is an equal likelihood that $a_{ij}^{k} = 1$ or $2\ \forall ijk$.
- All DNs are fully reconfigurable.
- If WCs are used, they are fully tunable and are deployed only in (G)ANs because of cost constraints.
- All optical nodes are dimensioned to handle any surges in traffic demand.
- All connections meet the transmission-impairment constraints [32,33].

At the end of each simulation run, recorded observations of λ_R are made for each of the pure, semihybrid, or hybrid WDM cases. Furthermore, the same simulation runs were carried out for cases in which WCs are present. The distribution of λ_R for all considered cases obtained after 100,000 trial simulation runs is shown in Fig. 5. From the distribution plots produced, the various statistical parameters were evaluated to compare the different simulated cases. The third quartile Q_3 (the value below which 75% of the trials appear) of the distribution could be considered to represent the minimum wavelength requirement in this study. Also of interest is the range $\Re$ of λ_R (difference between minimum and maximum λ_R) as it influences the complexity (number of constituent component modules) of networks nodes. This is especially crucial for ANs that tend to switch, route, add, or drop tightly packed wavelength channels. A large $\Re$ requires a deployment of a large number of component modules (e.g., WCs, switches, filters) that may be underutilized because extreme surges in demand for connections occur only for a small fraction of the network's operational time.



(a)

(b)

(c)

(d)

(e)

Fig. 5. Distribution of λ_R for the example network when (a) pure WDM (b) semihybrid WDM ($N = 4$), (c) semihybrid WDM ($N = 16$), (d) hybrid WDM ($N = 4$), and (e) hybrid WDM ($N = 16$) schemes are used.

From Fig. 5(a), pure WDM Q_3 is approximately 87 and $\Re = 106$ wavelengths. By contrast, if semihybrid WDM (with $N = 4$) is used instead, then Q_3 is now 63 and $\Re = 82$. For the same WDM scheme, when N is quadrupled to 16, the changes are negligible ($Q_3 = 63$ and $\Re = 80$) as shown in Fig. 5(c). However, the improvements provided by hybrid WDM are more significant [Figs. 5(d) and 5(e)]. In this case, the wavelength parameters of interest ($Q_3 = 29$ and $\Re = 32$) are just over a quarter of those observed for pure WDM. Furthermore, when N is quadrupled, the fluctuations in the parameters are more noticeable ($Q_3 = 21$ and $\Re = 28$) unlike in the semihybrid WDM case.

The use of WCs in ANs greatly enhances the flexibility of resource allocation and wavelength reuse. Results obtained from the simulation of networks with WCs confirm this observation (see Fig. 5). Improvements are significant in both extreme cases, whereby for pure WDM and hybrid WDM ($N = 16$) schemes, the parameters of interest are ($Q_3 = 44$ and $\Re = 47$) and ($Q_3 = 11$ and $\Re = 7$), respectively. Such improvements easily translate into large savings in cost and leaves plenty of room for future growth in traffic.

5. Discussion

In this paper, the allocation of wavelengths for networks with both fixed and wireless connected end users has been analyzed. Three different cases were simulated: pure WDM, semihybrid WDM, and hybrid WDM. From the simulation results, although pure WDM is technically the easier to implement, it makes inefficient use of wavelength channels, complicates network node architectures, and requires an unacceptably large number of optical transceivers. In contrast, hybrid WDM requires the least number of wavelengths; however, the (de)multiplexing and routing of mixed signal streams from both FAPs and RAPs is a nontrivial engineering task. Semihybrid WDM is considered to be a compromise solution of the aforementioned schemes, by reduction of the wavelength-channel requirement with simpler multiplexing solutions.

It was further observed from the simulations that a limited deployment of WCs eased the wavelength requirement, especially when the pure WDM scheme is used. However, the practical implementation of WCs is still confined to experimental testbeds because of various practical limitations (e.g., high cost, limited tunability, polarization dependence, amplitude distortions) [21]. Ultimately, the choice of WDM scheme will be dependent on the consideration of various factors that include cost, ease of implementation, technical feasibility, type of AP, technological advances (especially optical integrated circuits), and customer numbers. For the time being, the ETDM/WDM is expected to remain the dominant scheme. However, in the future, optimum solutions using different WDM schemes within same MAN may be the preferred option. A further possibility would be the implementation of multilevel hybrid WDM (e.g., ETDM/OCDM/WDM) that would reduce λ_R even further.

From this study, one thing is clear: The burden on optical resource provision due to future-generation (4G and beyond) wireless networks will be significant. However, the revenue potential created for both optical network operators (additional traffic from wireless customers) and wireless operators (increased reach and backhaul capacity) calls for ways to improve the interworking between the two network types. The optimal provisioning of optical resources as expounded in this paper is just one of the many issues that require further study.

Acknowledgments

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References and Links

[1] A. Saleh and J. M. Simmons, "Architectural principles of optical regional and metropolitan access networks," IEEE J. Lightwave Technol. **17,** 2431–2448 (1999).

[2] B. Khasnabish, "Broadband to the home BTTH: architectures, access methods and the appetite for it," IEEE Netw. **11,** 58–69 (1997).

[3] P. Smulders, "Exploiting the 60 GHz band for local wireless multimedia access: prospects and future directions," IEEE Commun. Mag. **40,** 140–147 (2002).

[4] H. Kawamura, N. Imai, E. Ogawa, and H. Inomata, "High-speed data transmission using millimeter-wave fiber-optic links," IEICE Trans. Commun. **E79-B,** 1784–1791 (1996).

[5] K. Kitayama, A. Stohr, T. Kuri, R. Heinzelmann, D. Jager, and Y. Takahashi, "High-speed data transmission using millimeter-wave fiber-optic links," IEEE Trans. Microwave Theory Tech. **48,** 2588–2595 (2000).

[6] T. E. Stern and K. Bala, *Multiwavelength Optical Networks: A Layered Approach* (Addison-Wesley, Reading, Pa., 1999).

[7] O. Morales, "IP over Ethernet via fiber," IT Prof. **3,** 43–45 (2001).

[8] C. R. Giles and M. Spector, "The wavelength add/drop multiplexer for lightwave communication networks," Bell Lab. Tech. J. **4,** 207–229 (1999).

[9] M. Medard and S. Lumetta, "Architectural issues for robust optical access," IEEE Commun. Mag. **39,** 116–122 (2001).

[10] Y. Cao, "Internetworking with the intelligent optical layer," J. Opt. Netw. **1,** 129–142 (2002), http://www.osa-jon.org/abstract.cfm?URI=JON-1-3-129.

[11] T. Flower, "Mesh networks for broadband access," IEE Rev. **47,** 17–22 (2001).

[12] M. Hānnikāinen, T. D. Hāmālāinen, M. Niemi, and J. Saarinen, "Trends in personal wireless data communications," Comp. Commun. **25,** 84–99 (2002).

[13] R. Becher, M. Dillinger, M. Haardt, and W. Mohr, "Broadband wirelesss access and future communications networks," Proc. IEEE **89,** 58–75 (2001).

[14] A. Bria, F. Gessler, O. Queseth, R. Stridh, M. Unbehaun, W. Jiang, J. Zander, and M. Flament, "4th-generation wireless infrastructures: scenarios and research challenges," IEEE Personal Commun. Mag. **8,** 25–31 (2001).

[15] S. Weinstein, "The mobile Internet: Wireless LAN vs. 3G cellular mobile," IEEE Commun. Mag. **40,** 26–27 (2002).

[16] W. Webb, "Broadband fixed wireless access as a key component of the future integrated communications environment," IEEE Commun. Mag. **39,** 115–121 (2001).

[17] IEEE Standard 802.16, "IEEE standards for local and metropolitan area networks: air interface for fixed broadband wireless access systems" (Institute of Electrical and Electronics Engineers, 2001), http://www.ieee.org.

[18] P. J. Legg and P. Crichton, "ACTS MEDIAN: a wireless LAN supporting ATM at 155 Mb/s," in *IEE Colloquium on ATM Traffic in the Personal Mobile Communications Environment* (Institute of Electrical and Engineers, London, 1997), pp. 1–5.

[19] A. Seeds, "Microwave photonics," IEEE Trans. Microwave Theory Tech. **50,** 877–887 (2002).

[20] H. Zang, J. P. Jue, and B. Murkhejee, "A review of routing and wavelength assignment approaches for wavelength assignment approaches for wavelength-routed optical WDM networks," Opt. Netw. Mag. **5,** 47–60 (2000).

[21] J. M. H. Elmirghani and T. H. Mouftah, "All-optical wavelength conversion: technologies and applications in DWDM networks," IEEE Commun. Mag. **38,** 86–92 (2000).

[22] T. S. El-Bawab and J.-D. Shin, "Optical packet switching in core networks: between vision and reality," IEEE Commun. Mag. **40,** 60–65 (2002).

[23] G. Grosskopf, B. Sartorius, B. Bornholdt, B. Kuhlow, G. Przyrembel, S. Zinal, D. Rohde, R. Eggemann, J. Slovak, and M. Mohrle, "60 GHz-millimetre-wave generation and beam-forming in hybrid-fibre-radio systems for broadband-wireless access," in *27th Triennial General Assembly of the International Union of Radio Science* (URSI, Maastricht, 2002), pp. D1.0.2.

[24] J. J. O'Reilly, P. M. Lane, J. Attard, and R. Griffin, "Broadband wireless systems and networks: an enabling role for radio-over-fibre," Philos. Trans. R. Soc. London Ser. A **358,** 2297–2308 (2000).

[25] R. Hui, B. Zhu, R. Huang, C.T. Allen, K. R. Demarest, and D. Richards, "Subcarrier multiplex-

ing for high-speed optical transmission," IEEE J. Lightwave Technol. **20,** 417–427 (2002).

[26] T. Kamisaka, T. Kuri, and K. Kitayama, "Simultaneous modulation and fiber-optic transmission of 10-Gb/s baseband and 60-GHz-band radio signals on a single wavelength," IEEE Trans. Microwave Theory Tech. **49,** 2013–2017 (2001).

[27] G. Smith, D. Novak, and C. Lim, "A millimeter-wave full-duplex fiber-radio star-tree architecture incorporating WDM and SCM," IEEE Photon. Technol. Lett. **10,** 1650–1652 (1998).

[28] P. Bayvel, "Future high-capacity optical telecommunications network," Philos. Trans. R. Soc. London Ser. A **358,** 303–329 (2000).

[29] S. Bigo, Y. Frignac, G. Charlet, W. Idler, S. Borne, H. Gross, R. Dischler, W. Poehlmann, P. Tran, C. Simonneau, D. Bayart, G. Veith, A. Jourdan, and J.-P. Hamaide, "10.2 Tbit/s (256x42.7 Gbit/s PDM/WDM) transmission over 100 km TeraLight/sup TM/ fiber with 1.28 bit/s/Hz spectral efficiency ," in *Optical Fiber Communication Conference (OFC 2001),* Vol. 54 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2001), paper PD25-1.

[30] K. Kitayama, H. Sotobayashi, and N. Wada, "Optical code division multiplexing (OCDM) and its applications to photonics networks," IEICE Trans. Commun. **E82-A,** 2616–2626 (1999).

[31] G. Li and R. Simha, "On the wavelength assignment problem in multifiber WDM star and ring networks," IEEE/ACM Trans. Netw. **9,** 60–68 (2001).

[32] B. Ramamurthy, D. Datta, H. Feng, J. P. Heritage, and B. Mukherjee, "Impact of transmission impairments on the teletraffic performance of wavelength-routed optical networks," IEEE J. Lightwave Technol. **17,** 1713–1723 (1999).

[33] E. Mutafungwa, "Optical hop number limits imposed by various 2 × 2 cross-connect node designs," Opt. Express **9,** 400–410 (2001), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-9-8-400.