Hybrid Wireless-Optical Broadband-Access Network (WOBAN): A Review of Relevant Challenges

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(Invited Paper)

***Abstract*—The hybrid wireless-optical broadband-access network (WOBAN) is a promising architecture for future access networks. Recently, the wireless part of WOBAN has been gaining increasing attention, and early versions are being deployed as municipal access solutions to eliminate the wired drop to every wireless router at customer premises. This architecture saves on network deployment cost because the fiber need not penetrate each end-user, and it extends the reach of emerging optical-access solutions, such as passive optical networks. This paper first presents an architecture and a vision for the WOBAN and articulates why the combination of wireless and optical presents a compelling solution that optimizes the best of both worlds. While this discussion briefly touches upon the business drivers, the main arguments are based on technical and deployment considerations. Consequently, the rest of this paper reviews a variety of relevant research challenges, namely, network setup, network connectivity, and fault-tolerant behavior of the WOBAN. In the network setup, we review the design of a WOBAN where the back end is a wired optical network, the front end is managed by a wireless connectivity, and, in between, the tail ends of the optical part [known as optical network unit (ONU)] communicate directly with wireless base stations (known as "gateway routers"). We outline algorithms to optimize the placement of ONUs in a WOBAN and report on a survey that we conducted on the distribution and types of wireless routers in the Wildhorse residential neighborhood of North Davis, CA. Then, we examine the WOBAN's routing properties (network connectivity), discuss the pros and cons of various routing algorithms, and summarize the idea behind fault-tolerant design of such hybrid networks.**

***Index Terms*—Architecture, broadband access, fault tolerance, optical network, routing, wireless network.**

I. Introduction

THE DOMINANT broadband-access network that is emerging from today's research and development activities is a point-to-multipoint (P2MP) optical network known as passive optical network (PON). The basic configuration of a PON connects the telecom central office (CO) to businesses and residential users by using one wavelength channel in the downstream direction [from optical line terminal (OLT) at CO to optical network units (ONUs)] and another wavelength channel in the upstream direction [from ONUs to OLT]. A PON does not have any active element in the signal's path from source to destination; hence, it is robust. The only interior elements used in such a network are passive combiners, couplers, and splitters.

A PON provides much higher bandwidth for data applications [than current solutions such as digital subscriber line (DSL) and cable modem (CM)], as well as deeper fiber penetration. Based on current standards, a PON can cover a maximum distance of 20 km from the OLT to the ONU. While fiber-to-the-building, fiber-to-the-home (FTTH), or even fiber-to-the-PC solutions have the ultimate goal of fiber reaching all the way to end-user premises, fiber-to-the-curb may be a more economical deployment scenario today [1], [2].

The traditional single-wavelength PON (also known as the time-division-multiplexed PON or TDM-PON) combines the high capacity of optical fiber with the low installation and maintenance cost of a passive infrastructure. The optical carrier (OC) is shared by means of a passive splitter among all the users, so the PON topology is a tree, as in most other distribution networks, e.g., those for power, voice, video, etc. As a consequence, the number of ONUs is limited by the splitting loss and by the bit rate of the transceivers in the OLT and in the ONUs. Current specifications allow for 16 ONUs at a maximum distance of 20 km from the OLT and 32 ONUs at a maximum distance of 10 km from the OLT.

The per-user cost of such a network can be low as the bandwidth (typically up to 1 Gb/s in current practice and expected to increase to 10 Gb/s in the future) is shared among all the end users, but, as end users demand more bandwidth, the need to upgrade the existing PON architectures [viz., Ethernet PON (EPON), Broadband PON (BPON, based on ATM), Gigabit PON (GPON), Generic Framing Procedure PON (GFP-PON), etc.] to Wavelength-Division-Multiplexed PON (WDM-PON) is essential. A WDM-PON solution provides excellent scalability because it can support multiple wavelengths over the same fiber infrastructure, it is inherently transparent to the channel bit rate, and, depending on its architecture, it may not suffer power-splitting losses (see [3] for a review of WDM-PON architectures).

Manuscript received February 15, 2007; revised May 10, 2007.

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Digital Object Identifier 10.1109/JLT.2007.906804

The straightforward approach to build a WDM-PON is to employ a separate wavelength channel from the OLT to each ONU, both in the upstream and downstream directions. This approach creates a point-to-point (P2P) link between the OLT and each ONU, which differs from the P2MP topology of the traditional PON. In the WDM-PON, each ONU can operate at a rate up to the full bit rate of a wavelength channel. Moreover, different wavelengths may be operated at different bit rates, if necessary; hence, different types of services may be supported over the same network. This is clearly an advantage of WDM-PON over the traditional PON [4].

There are various industry efforts to build PON architecture for commercial deployment. In the United States, Verizon has introduced its "Fiber-to-the-Premises" architecture, called FiOS, to deliver high-speed voice and data services to the home. FiOS service consists of three consumer broadband speeds: up to 5 Mb/s downstream and up to 2 Mb/s upstream (5 Mb/s/2 Mb/s), 15 Mb/s/2 Mb/s, and 30 Mb/s/5 Mb/s. The FiOS network is migrating from current BPON to future GPON architecture, thus moving toward higher upstream/downstream speed and eliminating ATM [5]. Among other efforts, Novera Optics has launched TurboLIGHT, a dense-WDM fiber-to-the-X optical-access technology, which allows flexible multimode-transport capabilities at different bit rates (125 Mb/s–1.25 Gb/s) [6]. In Asia, a similar effort can be found in WE-PON, which has a combined architecture of WDM (from CO to WDM device) and TDM (from WDM device to ONU through splitters) with bit rates on the order of 100 Mb/s [7].

Another promising access solution is a wireless network. Recently, we have seen tremendous growth in the research and deployment of various wireless technologies. There are three major techniques that have been employed for wireless-access networks worldwide, viz., "Wireless Fidelity" (known as WiFi), "Worldwide Interoperability for Microwave Access" (known as WiMax), and "Cellular Network." These technologies have their own advantages and disadvantages.

WiFi is one of the most popular wireless technology (standards: IEEE 802.11a/b/g), and it is mainly used for wireless local-area networks. WiFi can operate in both the "Infrastructure" and "*Ad Hoc*" modes. In infrastructure mode, a central authority, known as access point, is required to manage the network. But, in *ad hoc* mode, the users are self-managed, and there is no concept of an administrator. WiFi technology can exploit the flexibility of "multihopping." WiFi offers low bit rate (max 54/11/54 Mb/s for 802.11a/b/g, respectively) and limited range (typically 100 m).

WiMax (standard: IEEE 802.16) is gaining rapid popularity. It is essentially a P2MP broadband wireless-access service. WiMax can be used efficiently for single-hop communication (for multihop, WiMax suffers from higher delay and lower throughput). It provides high bandwidth and uses less-crowded spectrum. Thus, WiMax is particularly suitable for wireless metropolitan-area networks because of its high bit rate and long range. It can support data rates up to 75 Mb/s in a range of 3–5 km and, typically, 20–30 Mb/s in longer ranges. Transmission over longer distances significantly reduces bit rates due to the fact that WiMax does not work efficiently for nonline-of-sight communications. WiMax base stations (BSs) can be placed indoor (installed by customer) or outdoor (installed by network operator) to manage the wireless network. Recently, WiMax is being examined as an alternative for fixed-wired infrastructures, viz., DSL and CM, to deliver "last mile" broadband access to users.

Cellular technology is used for low-bit-rate applications (maximum of 2 Mb/s). A cellular network is mainly used to carry voice traffic and is unoptimized for data traffic. In addition, the data component of the cellular network, such as the high-speed downlink packet access and high-speed uplink packet access, jointly known as high-speed packet access (HSPA) in the third-generation (3G) evolution, can deliver a downstream bandwidth of up to 14 Mb/s and upstream bandwidth of 5 Mb/s. A more advanced version, namely, HSPA+, will offer a downlink speed of up to 40 Mb/s and up to 10 Mb/s in upstream direction. They use Federal Communications Commission regulated expensive spectrum (licensed band) with 3G, beyond-third-generation (B3G), and fourth-generation (4G) standards. WiFi technology, on the other hand, uses the free industrial, scientific, and medical (ISM) band, while WiMax uses both licensed and ISM bands.

There are several industry efforts to build WiMax architecture for commercial deployment, and a few examples are stated as follows. In the U.S., Sprint Nextel holds the license in 2.5-GHz band to build a nationwide wireless-access network, which is expected to cover 100 million U.S. customers in 2008 [8]. Towerstream has deployed wireless networks, which have bit rates of tens of megabits per second, in several locations in the U.S. [9]. Among other regions, Intel WiMax trials have been launched in several locations in Europe and India in collaborations with local service providers [10].

The growing customer demands for bandwidth-intensive services (such as "Quad-play," which refers to voice, video, Internet, and wireless—all are delivered over IP whether on a fixed, mobile, or a hybrid access infrastructure to bring operational efficiencies and convenience to end-users) are accelerating the research efforts needed to design an efficient "last mile" access network in a cost-effective manner. Thus, the radio-on-fiber (ROF) technology has gained momentum, where radio signals can be effectively carried over an existing optical-fiber infrastructure (saving "last mile" costs) by means of the "hybrid fiber radio" (HFR) enabling technology. Recent research works propose ROF-based technologies in millimeter-waveband [11], [12] and demonstrate integrated broadband services in a ROF downstream link [13]. HFR helps to reduce the design complexity at the remote antenna units (RAU) (consequently leading to cheap and simple RAUs), because up/down-conversion, multiplexing/demultiplexing, modulation/demodulation, etc. can be performed at a CO (also known as HFR head end). It is also possible to transmit multiple radio signals over the same fiber. The ROF-enabled access network may have different topologies, such as "optical star–radio P2P," "optical tree–radio star," "optical star–radio cellular," etc. Among various research efforts, Lin [14] proposes a dynamic wavelength-allocation scheme at the bursty traffic load for WDM fiber-radio ring access networks. Reference [15] demonstrates simultaneous wireline (600 MHz) and wireless (5.5 GHz) data transmission in a hybrid fiber-radio access network over cable-service

TABLE I
SAMPLE OF MUNICIPAL MESH NETWORKS

Area/Location	Architecture	Compatibility		Configuration	Operating Range	Player
		Present	Future			
Akron, OH	Flat AP infrastructure	WiFi	WiFi	Multiple radio	2.4 GHz	MobilePro
Athens, GA	Multi-layered MP2P	WiFi	WiFi, WiMax	Multi-radio	2.4, 5 GHz	Belair
Bristol, UK	Multi-layered deployment	WiFi	WiFi, WiMax	Multi-radio multi-antenna	2.4, 5 GHz	Belair
Chaska, MN	Flat deployment	WiFi	WiFi, WiMax	Single radio (omni-directional)	2.4 GHz	Tropos, Pronto
Corpus Christi, TX	Flat deployment (GPS-compatible)	WiFi	WiFi	Single radio (omni-directional)	2.4 GHz	Tropos, Pronto
Culver City, CA	Flat (intermesh capable)	WiFi	WiFi	Multi-radio omni-directional	2.4, 5 GHz	Firetide
Farmers Branch, TX	Gateways with OC-3 ingress	WiFi	WiFi, WiMax	Multiple radio	2.4, GHz	NeoReach, Pronto
Galt, CA	Multi-layered deployment	WiFi	WiFi, WiMax	Multi-radio multi-antenna	2.4, 5 GHz	Belair
Gilbert, AZ	Flat AP infrastructure	WiFi	WiFi	Multiple radio	2.4 GHz	MobilePro
Gordes, France	Flat with intermesh	WiFi	WiFi	Multi-radio omni-directional	2.4, 5 GHz	Firetide
Isla Vista, CA	Flat deployment	WiFi	WiFi	Multi-radio	2.4, 5 GHz	Firetide
Islington, UK	3-tier hierarchical deployment	WiFi	WiFi	Multi-radio multi-antenna	2.4, 5 GHz	Belair
Moorehead, MN	P2MP with fiber optic backbone	WiFi	WiFi	Single radio (omni-directional)	2.4 GHz	Tropos
New Orleans, LA	WiFi routers with digital IP cameras attached to IP-backbone for video surveillance system					Tropos
Philadelphia, PA	Currently being deployed					Earthlink
San Francisco, CA	Currently being deployed					Earthlink, Google
Springfiled, MO	Hierarchical (L2 VLAN capable)	WiFi	WiFi	Multi-radio	2.4, 5 GHz	Belair
St. Maarten, Carribean	Hierarchical deployment	WiFi	WiFi	Multi-radio	2.4, 5 GHz	Belair, Lucent
Tempe, AZ	Gateways with OC-3 ingress	WiFi	WiFi, WiMax	Multi-radio multi-antenna	2.4, 5 GHz	Strix, NeoReach
Wavion, Inc. is a new player with their "spatially adaptive" MIMO-based routers having an antenna array and six radio transreceivers.						

interface specification, and a scheme for quantizing radio signals over fiber is investigated in [16]. A good overview of cost-effective wireless-over-fiber technology is provided in [17].

The rest of this paper is organized as follows. Section II reviews a novel architecture for broadband-access solution [called "hybrid wireless-optical broadband-access network (WOBAN)"], which captures the best of both the optical and wireless worlds and articulates the motivation behind WOBAN. It also summarizes (in Table I) the business drivers deploying an early incarnation of this network all over the world. In Section III, we briefly discuss and evaluate the algorithms for WOBAN deployment (network setup). In addition, some representative data from our survey of locations and types of wireless users in the Wildhorse residential neighborhood of North Davis, CA, are also examined. In Section IV, we discuss the routing characteristics of a WOBAN and study the pros and cons of various routing algorithms. Section V discusses the fault-tolerant behavior of a WOBAN, and Section VI concludes this paper.

This paper reviews in brief our research works on WOBANs (for more details, see the following papers: [18] and [19] for details on the WOBAN architecture presented in Section II; [18]–[20] for details on the WOBAN's network setup problem discussed in Section III; [21] for details on the WOBAN's routing problems and algorithms studied in Section IV; and [22] for details on the WOBAN's fault-tolerant properties outlined in Section V.

II. NOVEL WOBAN ARCHITECTURE

The concept of a hybrid WOBAN is a very attractive one. This is because it may be costly in several situations to run fiber to every home (or equivalent end-user premises) from the telecom CO; in addition, providing wireless access from the CO to every end-user may not be possible because of limited spectrum. Thus, running fiber as far as possible from the CO toward the end-user and then having wireless-access technologies take over may be an excellent compromise. How far should fiber penetrate before wireless takes over is an interesting engineering design and optimization problem.

The WOBAN architecture can be employed to capture the best of both worlds: 1) the reliability, robustness, and high capacity of wireline optical communication and 2) the flexibility ("anytime–anywhere" approach) and cost savings of a wireless network. A WOBAN consists of a wireless network at the front end, and it is supported by an optical network at the back end (see Fig. 1). Noting that the dominant optical-access technology today is the PON, different PON segments can be supported by a telecom CO, with each PON segment radiating away from the CO. Note that the head end of each PON segment is driven by an OLT, which is located at the CO. The tail end of each PON segment will contain a number of ONUs, which typically serve end-users in a standard PON architecture. However, for the proposed hybrid WOBAN, the ONUs will connect to wireless BSs for the wireless portion of the WOBAN. The wireless BSs that are directly connected to the ONUs are known as wireless "gateway routers," because they are the gateways of both the optical and the wireless worlds. Besides these gateways, the wireless front end of a WOBAN consists of other wireless routers/BSs to efficiently manage the network. Thus, the front end of a WOBAN is essentially a multihop wireless mesh network with several wireless routers and a few gateways (to connect to the ONUs and, consequently, to the rest of the Internet through OLTs/CO). The wireless portion of the WOBAN may employ standard technologies such as WiFi or WiMax. Since the ONUs will be located far away from the CO, efficient spectrum reuse can be expected across the BSs with much smaller range but with much higher bandwidth; thus, this WOBAN can potentially support a much larger user base with high bandwidth needs.

In a typical WOBAN, end-users, e.g., subscribers with wireless devices at individual homes, are scattered over a geographic area. An end-user sends a data packet to one of its neighborhood wireless routers. This router then injects the packet into the wireless mesh of the WOBAN. The packet

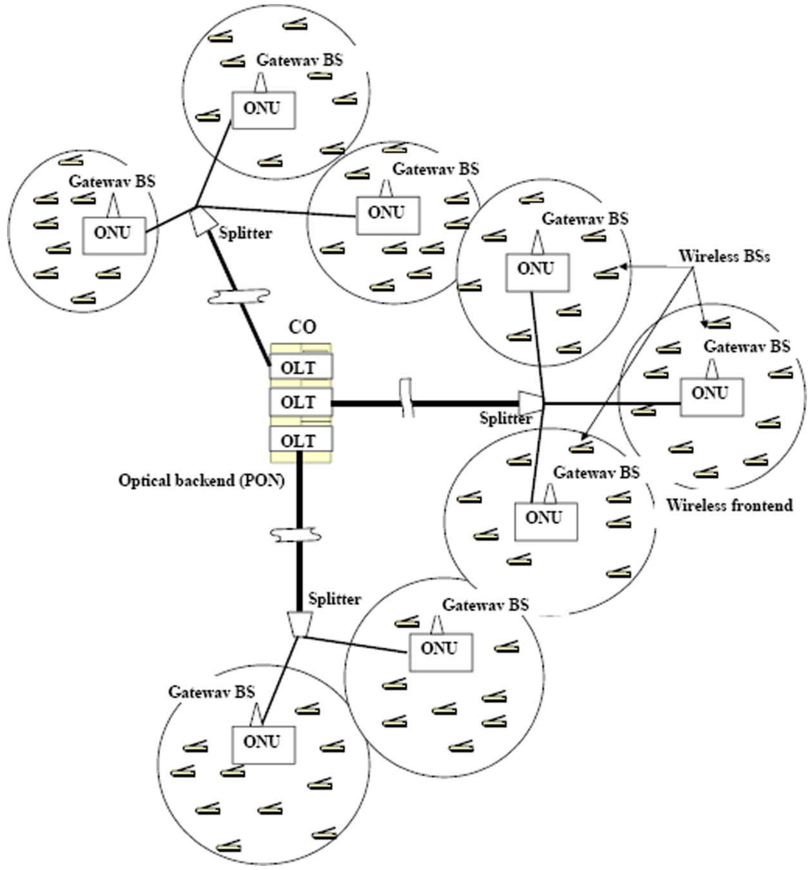

Fig. 1. Hybrid WOBAN architecture.

travels through the mesh, possibly over multiple hops, to one of the gateways (and to the ONU) and is finally sent through the optical part of the WOBAN to the OLT/CO. In the upstream direction of the wireless front end (from a wireless user to a gateway/ONU), the WOBAN is an anycast network, i.e., an end-user can try to deliver its packet(s) to any one of the gateways (from which the packet will find its way to the rest of the Internet). In the optical back end, the upstream (from an ONU to an OLT/CO) of a WOBAN is a multipoint media-access network, where ONUs are deployed in a tree network with respect to their OLT, and they contend for a shared upstream resource (or bandwidth), but in the downstream direction of the wireless front end (from a gateway/ONU to a wireless user), this network is a unicast network, i.e., a gateway will send a packet to only its specific destination (or user). In the optical back end, the downstream (from an OLT/CO to an ONU) of a WOBAN is a broadcast network, where a packet, destined for a particular ONU, is broadcast to all ONUs in the tree and processed selectively only by the destination ONU (all other ONUs discard the packet), as in a standard PON [1]. Fig. 2 captures a WOBAN's upstream- and downstream-transmit modes. A research proposal has been made for a bandwidth-allocation algorithm for an interactive video-on-demand system over a hybrid optical-wireless network in [23].

The WOBAN architecture assumes that an OLT is placed in a telecom CO and that it feeds several ONUs. Thus, from ONU to the CO, we have a traditional fiber network; moreover,

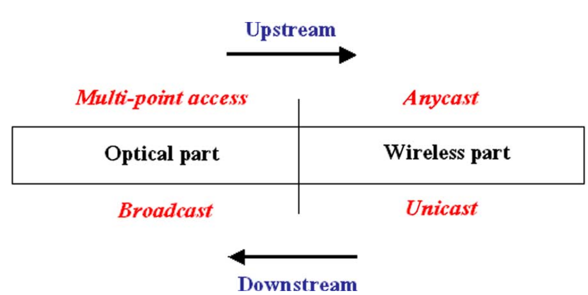

Fig. 2. WOBAN's upstream and downstream protocols.

from ONUs, end-users are wirelessly connected (in single-hop or multihop fashion).

A common vision of a next-generation converged (fixed and wireless) network is that of the IP-based end-to-end (between the end nodes) network, which enables devices to access common services over one or more networks seamlessly. In a WOBAN, end terminal mobility can be supported at the IP layer by one of the three dominant approaches developed at the Internet Engineering Task Force (IETF), namely, mobile IP, migrate, and host-identity protocol. Mobile IP has unquestionably received the most attention and has already been demonstrated to work well in large networks [24]. Since mobility at the IP layer is an overlay protocol and can be easily supported on a WOBAN, we do not cover it in this paper.

A. Motivation Behind WOBAN

The advantages of a WOBAN over the wireline optical and wireless networks have made the research and deployment of this type of network more attractive. These advantages can be summarized as follows.

1) A WOBAN can be very cost effective as compared to a wired network. The architecture (see Fig. 1) demonstrates that we do not need expensive "FTTH" connectivity, because installing and maintaining the fiber all the way to each user could be quite costly (note that, according to the 2001 U.S. census figures, there are 135 million houses in the U.S., and the estimates are that to wire 80% of the U.S. households with broadband would cost anywhere between $60–120 billion, whereas with wireless, the estimates are that it would cost only $2 billion). In WOBAN, a user will connect to its neighborhood ONU in a wireless fashion, possibly over multiple hops through other wireless routers. At the ONU, the wireless user's data will be processed and sent to the OLT using the optical-fiber infrastructure.
2) The wireless part of this architecture allows the users inside the WOBAN to seamlessly connect to one another. Therefore, a WOBAN is more flexible than the optical-access network. The "anytime–anywhere" approach is also applicable to the WOBAN. Thus, WiFi is a convenient technology for the front end of the WOBAN so that we can exploit its flexibility and multihopping capability. WiMax is an alternative (to WiFi) for the front end of WOBAN, in which, apart from its flexibility, we can also take advantage of its higher bit rate as compared to WiFi.
3) A WOBAN should be more robust than the traditional wireline network. In a traditional PON, if a fiber connecting the splitter to an ONU breaks (see Fig. 1), that ONU will be down. Even worse, if a trunk from OLT to the splitter breaks, all the ONUs (along with the users served by the ONUs) will fail, but in a WOBAN, as the users have the ability to form a multihop mesh topology, the wireless connectivity may be able to adapt itself so that users may be able to find a neighboring ONU which is alive. Then, the users can communicate with that ONU and, that ONU, in turn, will communicate with another OLT in the CO.
4) Due to its high-capacity optical trunk, the WOBAN will have much higher capacity than the relatively low capacity of the wireless network.
5) A WOBAN will be more reliable than the wireless network. This, in turn, will help in reducing the problem of congestion and information loss in a WOBAN as compared to the current wireless network. In addition, a user's ability to communicate with any other ONU in its vicinity, if its primary ONU breaks or is congested, gives the WOBAN a better load-balancing capability.
6) The WOBAN is "self-organizing" because of its fault-tolerant capability [item 3) above] and because of its robustness with respect to network connectivity and load balancing features [item 5) above].
7) In many developing regions of the world, fiber is deeply deployed (within 20 km), even in the rural areas, but the cost to provide wireline broadband connectivity is prohibitively expensive, time consuming, and difficult to maintain. In such scenarios, the governments have decided to either build or provide incentives to the operators to deploy WOBAN-like architectures.

Noting that a WOBAN is a high-capacity cost-effective broadband network, recently, its early incarnations are being deployed as an access solution in many cities around the world. We capture a sampling of the current activities of municipal mesh networks (or the wireless part of a WOBAN) in Table I [25]–[32]. Thus, a WOBAN deployment is an important development in today's network scenario. A WOBAN deployment is more challenging than only an optical- or a wireless-access-network deployment. This is because of the design interplay between two very diverse access technologies (optical and wireless). However, research on traditional access-network placements can be a good starting point for a WOBAN design.

In Table I, we observe that different network operators deploy different architectures for the front end (wireless part) of WOBAN. The simplest architecture is the flat deployment of wireless routers with a single radio and omnidirectional antenna. The gateway routers are connected to the wired back haul and, then, to the rest of the Internet. Some of these gateways also have OC ingress ports to connect to the optical part of the network. A few of the network operators deploy hierarchical or multilayered infrastructure for the front end of WOBAN. Wireless routers and gateways may also be equipped with multiple radios and directional antenna. Some of the routers are even equipped with "spatially adaptive" multiple-input–multiple-output-based antenna array. Advanced network features, viz., P2MP fiber-optic connections, L2 VLANs, and intermeshing through fiber, etc., are often embedded in the back end of WOBAN.

Since WOBAN is a marriage of two powerful techniques, there are a lot of interesting research and implementation challenges in network planning and operation, which we will discuss next.

III. Network Setup: A Review of Placement Algorithms in WOBAN

The network performance largely depends on the deployment of ONUs, i.e., the gateway routers where the optical and wireless parts meet. Proper deployment of ONUs is critical to the cost optimization of a WOBAN. To tackle this problem, we review placement algorithms for deploying multiple ONUs in a WOBAN. Given the locations of the wireless users, these algorithms focus on how to find the "good" placement of multiple ONUs in a cost-effective manner. In the following, we briefly touch upon the various algorithms of ONU placement and compare their pros and cons.

A. Random and Deterministic Approaches

Random placement of ONUs is the simplest way of deploying the network. This is a trial-and-error method, where, after

TABLE II
PROS AND CONS OF VARIOUS PLACEMENT SCHEMES IN WOBAN

Placement Scheme	Objective	Solution Quality	Processing time	Comments (in brief)
Random	Placements of Optical Network Units (ONU) in WOBAN.	Worse	Constant	Simple. Trial-and-error methods may be used.
Deterministic		Better	Constant	Works well for symmetric topology. Pre-determined placement. No prior optimization.
Greedy Algorithm		Good	Linear (in practical cases)	Low complexity. Divide-and-conquer heuristic. Good solution for uniform distribution of users.
Simulated Annealing		Improved over Greedy	Depends on convergence criteria	Combinatorial optimizer. Improved solution over Greedy. May not converge for discontinuous cost model.
MIP	Optimum setup of ONUs and BSs.	Optimal	Very high	Complex analytical solution. Considers several constraints. Model predicts setup costs in dollars.

dividing the network into multiple nonoverlapping regions, ONUs are sprinkled randomly in each region. This scheme does not return an optimized-cost setup and may not ensure proper connectivity (this is because, while sprinkling randomly, ONUs may bunch up in parts of the network, leaving other parts void).

Deterministic placement, on the other hand, is a predetermined scheme, where after dividing the network into multiple nonoverlapping regions, ONUs are placed in the "centers" of each region. Deterministic scheme works well for a symmetric network and has a much lower processing requirement. There is no prior optimization involved, and it does not fit well for a network with a nonuniform distribution of users.

B. Greedy Approach

The Greedy algorithm (Greedy) is a divide-and-conquer method to partition the network (see [18] for details). The goal of Greedy is to place ONUs in a WOBAN, such that the average cost over all users with respect to a neighborhood ONU is optimized. The algorithm starts with a given distribution of wireless users. These users are primarily in the residential and business premises, so they have little or no mobility. Greedy considers a number of predetermined points as possible initial candidates to place the ONUs. Then, it finds the distances of all ONUs with respect to a user (whose coordinates are known beforehand). For each user, Greedy forms an ordered set (in ascending order), with the user's distances from ONUs as the set's elements. Then, it identifies the primary ONU, which is the closest (minimum distance from the user). Finally, Greedy obtains a set of users for primary ONUs (call these users "premium users" for that ONU) and optimizes the placement of each primary ONU with respect to its premium users.

C. Combinatorial Optimization: Simulated Annealing (SA) Approach

The Greedy algorithm is a heuristic, which performs local optimization of an individual ONU after the identification of premium users for that ONU. The solution is not globally optimal. For improved solution, a better approach is needed. Next, we summarize how the ONU placement problem can be retrofitted to a combinatorial optimizer, viz., SA [33], [34].

In SA, the initial placement of ONUs is obtained by the Greedy algorithm as in [18] (known as initialization phase of SA). The purpose of this global optimization is to find the minimum average cost for all the users (not only the premium users) with respect to multiple ONUs. Therefore, SA relocates the ONUs with a small random amount (perturbation phase of SA). After perturbation, the algorithm calculates the new cost of ONU placement (cost-calculation phase of SA) and observes how the new cost of ONU deployment changes with respect to the old cost. If the new cost of deployment is lower, SA accepts the relocation of ONUs; otherwise, it accepts the relocation with a certain probability (acceptance phase of SA). SA iterates the same process until there is no further cost improvement (update phase of SA). Then, the algorithm is said to be in the "equilibrium state," where no more perturbation will reduce the cost of deployment any further (details of the SA algorithm can be found in [19]).

D. Joint Optimization: Mixed-Integer-Programming (MIP) Approach

A joint optimization approach considers the design-interplay between both optical and wireless domains together. A proper predeployment optimization strategy can actually save expensive optical and wireless resources (and, in turn, dollars) needed for this type of network. Thus, a MIP model has been investigated in [20].

MIP focuses on the optimum simultaneous placement of BSs and ONUs in the front end and the fiber layout from BSs to ONUs and from ONUs to OLT/CO in the back end. It explores an analytical model that considers the cost of ONUs and BSs, and the cost of laying fiber. This is a predeployment network-optimization scheme, where the cost of WOBAN design (e.g., in dollars) is minimized by placing reduced number of BSs and ONUs and planning an efficient fiber layout. In order for proper operations of a WOBAN, MIP model considers several constraints to be satisfied: BS and ONU installation constraints, user-assignment constraints, channel-assignment constraints, capacity constraints, and signal-quality and interference constraints. The network operators can derive their costs of WOBAN deployment from the MIP model.

We briefly summarize the performances of various placement algorithms in the WOBAN in Table II.

TABLE III
SMALL PART OF SCANNING RESULTS FROM WILDHORSE

Mode: "Infrastructure", Antenna: "Omni-directional"					
Note: (E/B)SSID: (Extended/Basic) Service Set Identifier					
WEP: Wired Equivalent Privacy, WPA: Wi-Fi Protected Access					
Location=(Lat(N),Long(W)): (Latitude(North), Longitude(West))					
Carrier	ESSID	BSSID	Bit-Rate	Security	Lat(N),Long(W)
802.11g	belkin54g	00:30:BD:FC:B6:5F	54 Mbps	WPA	38.564026,-121.723358
	2WIRE192	00:0D:72:6C:4D:A9	22 Mbps	WEP	38.563850,-121.722694
	Big Momma	00:30:AB:1E:49:A1	11 Mbps	None	38.564327,-121.721260
	iRJMZ	00:11:24:0B:78:EB	11 Mbps	WPA	38.564732,-121.720886
	2WIRE680	00:0D:72:CE:49:F9	11 Mbps	WEP	38.564110,-121.721100
	Go Kings	00:09:5B:C9:3B:E4	36 Mbps	WPA	38.563934,-121.720978
	Home1	00:D0:9E:F9:D1:A9	22 Mbps	WEP	38.563744,-121.721298
802.11a	NETGEAR	00:09:5B:4E:67:54	11 Mbps	WEP	38.567661,-121.716934
	Unwired00	00:09:5B:AA:E6:6C	11 Mbps	WEP	38.567108,-121.723747
	NETGEAR	00:09:5B:66:1C:02	54 Mbps	None	38.568245,-121.725220
We also measured relative signal and noise levels (not reported here to conserve space).					

Fig. 3. Placement of three ONUs in Wildhorse WOBAN (Top left cone: ONU1, Bottom center cone: ONU2, Top right cone: ONU3. Colored dots are residential wireless routers/users).

E. Survey on Wireless Users in Wildhorse, Davis, California

An extensive survey on the wireless devices in the Wildhorse neighborhood of North Davis are reported in [18] to observe how various placement algorithms perform in a real network. We summarize a part of the survey that helps us to better understand the performances of the various ONU-placement algorithms in a WOBAN.

The Wildhorse neighborhood is quite dense and has only residential homes in an area of approximately 1150 m $\times$ 950 m. A small portion of the collected data is shown in Table III, where we are primarily interested in the locations of users (the column that shows the latitude and longitude of a wireless user) and the type of the wireless devices (column that shows the carrier). Therefore, the users' distribution in the Wildhorse WOBAN is known before deploying the ONUs.

Next, we summarize a test result that captures the essence of placement algorithms from our performance studies reported in [18] and [19]. The results in Figs. 3 and 4 show the performance of the same set of ONU-placement schemes discussed at the beginning of this section with a scanned input of 310 Wildhorse wireless users. Emerging services indicate that a future digital home will need a peak bandwidth of 70 Mb/s [35]. In addition, it is expected that future ONUs will support 10 Gb/s of bandwidth (per wavelength channel). Thus, three ONUs are needed to support the future demands of Wildhorse users at peak hours.

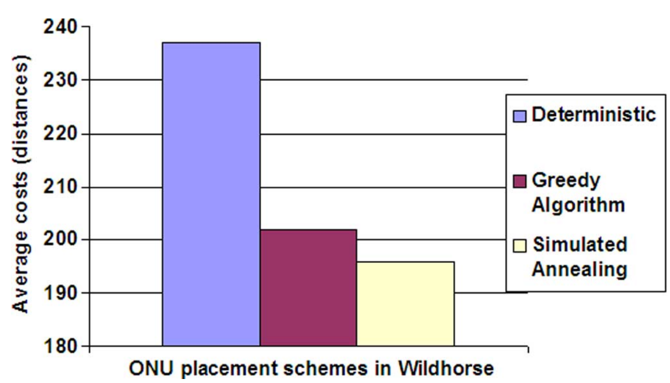

Fig. 4. Average costs (in meters) of ONU deployment in Wildhorse WOBAN.

We summarize the experiment to place three ONUs in the Wildhorse WOBAN. Fig. 3 shows the placement of the three ONUs (black triangles) in Wildhorse WOBAN through Greedy Algorithm. Their locations are (Latitude, Longitude) as follows: (38.5650N, $-$121.7197W), (38.5677N, $-$121.7254W), and (38.5690N, $-$121.7171W).

We also review a test result which compares various ONU-placement algorithms in Wildhorse WOBAN in Fig. 4, which shows the average cost (which is chosen to be the average distance between wireless users and their closest ONU) of ONU deployment in the Wildhorse WOBAN. We observe that the Greedy algorithm performs quite well, as compared to SA (only 2.7% off-the-range of the cost returned by SA), but at a much lower processing requirement. Here, the cost of random placement has not been shown as this cost is very high as compared to other schemes (e.g., Deterministic, Greedy, and SA). Detailed numerical examples can be found in [18] and [19]. The cost of joint optimization of ONUs and BSs can be found in [20].

IV. Network Connectivity: A Review of Routing Algorithms in WOBAN

Once the WOBAN is setup, how to efficiently route information (data packets) through it is an important and challenging problem. Note that the characteristics of a WOBAN's front-end wireless mesh are different from that of the traditional wireless mesh. In a traditional wireless mesh, the connectivity changes due to the users' mobility, and a wireless link goes up and down on-the-fly. On the other hand, since the WOBAN primarily is a network of residential and business users, its connectivity pattern in the wireless front-end can be preestimated.

An end-user sends a data packet to one of its neighborhood routers. This router then injects the packet into the wireless mesh of the WOBAN. The packet travels through the mesh, possibly over multiple hops, to one of the gateways/ONUs and is finally sent through the optical part of the WOBAN to the OLT/CO and then to the rest of the Internet. As discussed before, in the downstream direction, from OLT/CO to an ONU (back-end optical part), a WOBAN is a broadcast network, and from ONU/gateway to a user (front-end wireless part), a WOBAN is a unicast network. In the upstream direction, from a user to a gateway/ONU (front-end wireless part), a WOBAN is an anycast network, and from ONU to OLT/CO (back-end optical part), a WOBAN follows the traditional multipoint-access-control protocol to carry packets. Next, we briefly review the routing algorithms in the front-end wireless mesh of a WOBAN. These algorithms run inside each wireless router and gateway in the network.

A. Minimum-Hop and Shortest Path Routing Algorithms (MHRA and SPRA)

The MHRA and the SPRA are widely used in the wireless part of a WOBAN (because they are easy to implement), where the link metric in MHRA is unity, and in SPRA, it is generally inversely proportional to the link capacity. MHRA and SPRA work on the shortest path principle without generally considering other traffic demands on the network. Therefore, MHRA and SPRA could suffer from several routing limitations, viz., increased delay, poor load balancing, and high congestion in a link or along a segment (consisting of multiple links).

B. Predictive-Throughput Routing Algorithm (PTRA)

Recent approaches also consider solution providers' patented routing algorithms. PTRA is one such protocol (where PTRA is similar to "predictive wireless-routing protocol (PWRP)" [25]). We use the name "PTRA" instead of "PWRP" in this paper because the wording in PTRA is more expressive.

Unlike MHRA and SPRA, PTRA is not based on the shortest path routing principle. PTRA is a link-state-based routing scheme, and it chooses the path (from a set of possible paths between a user–gateway pair) that satisfies the overall throughput requirements, as explained next. PTRA takes measurement samples of link rates periodically across wireless links. Given a user–gateway pair, the algorithm computes available paths. Based on the history of samples, PTRA dynamically predicts link condition and then estimates the throughput of each path. It chooses the path that gives a higher estimated throughput [25]. Although PTRA is proposed and implemented for only carrying packets in the wireless part of a WOBAN, the major problem in PTRA is that the packet may end up traveling inside the mesh longer than expected (as PTRA does not take into account packet delay). Therefore, PTRA is not suitable for delay-sensitive services as the corresponding packets can take longer routes (as long as the route satisfies the throughput criteria).

C. Delay-Aware Routing Algorithm (DARA)

The routing in the wireless part of a WOBAN mesh deals with packets from a router to a gateway (and vice versa). A wireless routing path consists of two parts: 1) the associativity of a user to a nearby wireless router in its footprint and 2) the path from this (ingress) router to a suitable gateway (through the wireless mesh). DARA is a proactive routing approach that focuses on the packet delay (latency) in the front end (wireless mesh) of the WOBAN, i.e., the packet delay from the router to the gateway (attached to a ONU), and vice versa. The packet delay could be significant, as the packet may travel through several routers in the mesh before finally reaching the gateway (in the upstream direction) or to the user (in the downstream direction).

The larger the mesh of the WOBAN, the higher the expected delay will be. DARA approximately models each wireless router as a standard M/M/1 queue [36] and predicts the wireless-link states (using link-state prediction or LSP) periodically. Based on the LSP information, DARA assigns link weights to the wireless links. Links with higher predicted delays are given higher weights. Then, DARA computes the path with the minimum predicted delay from a router to any gateway and vice versa. While traveling upstream/downstream, a router/gateway will send its packet along the computed path only if the predicted delay is below a predetermined threshold, referred to as the delay requirement for the mesh; otherwise, DARA will not admit the packet into the mesh. DARA shows how choosing a path from a set of paths (whose delays are below the delay requirement) can alleviate congestion and achieve better load balancing. The details of DARA can be found in [21].

We briefly summarize the performance of the various routing algorithms in Table IV.

In the optical back end, traditional multipoint control protocol can be used in the upstream direction (from ONUs to OLT).

TABLE IV
PROS AND CONS OF VARIOUS ROUTING ALGORITHMS IN THE WIRELESS PART OF A WOBAN

Routing algorithm	Objective	Link prediction used	Alternative path used	Performance								
				Delay		Throughput		Hop count		Load balancing		Risk awareness
				H	L	H	L	H	L	H	L	
MHRA	Hop minimization; unity link weight.	No	No	√	×	√	×	√	√	×	×	No
SPRA	Shortest path; inverse-capacity link weight.	No	No	√	×	√	×	√	√	×	×	No
PTRA	Throughput optimization.	No	Yes	×	×	√	√	×	×	√	√	No
DARA	Delay minimization.	Yes	Yes	√	√	√	√	√	×	√	√	No
RADAR	Minimize delay and packet loss.	Yes	Yes	√	√	√	√	√	×	√	√	Yes

H: High load (0.5-0.95), L: Low load (0.0-0.49)

√: Algorithm performs well, ×: Algorithm performs poorly.

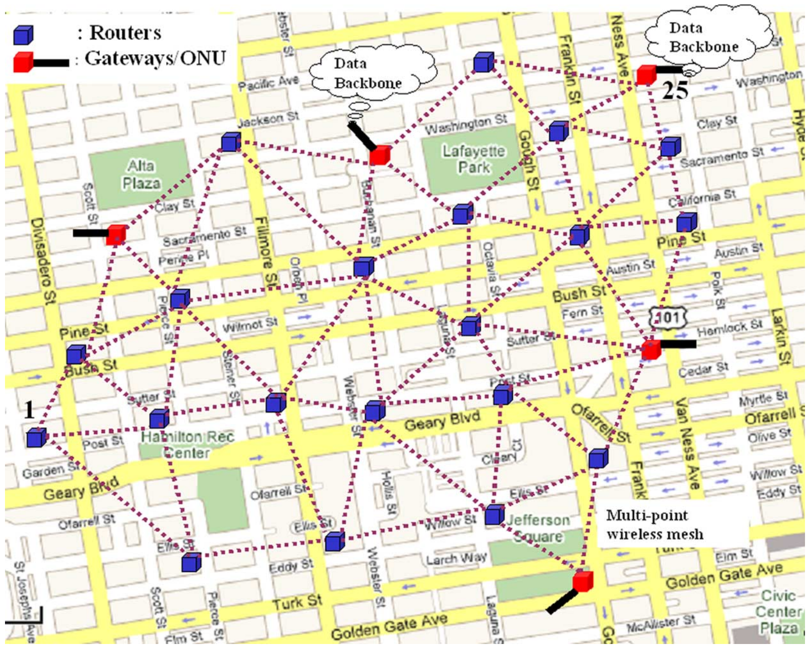

Fig. 5. SFNet: Wireless mesh in San Francisco WOBAN.

Wireless gateways continue to send the packets to an ONU, and the ONU, after accumulating several packets from gateways, will send a REPORT message to the OLT (indicating its volume of accumulated packets). The OLT, on getting this REPORT, grants a portion of the shared upstream bandwidth to the ONU through a GATE message. On the other hand, the downstream of optical back end in a WOBAN (OLT to ONUs) can be a broadcast network, where a packet from OLT is broadcast to all the ONUs in its downstream tree but only the destination ONU will "selectively" process the packet while other ONUs will discard it, as in a traditional PON architecture [2].

D. Study on San Francisco WOBAN

A study on the San Francisco WOBAN (called "SFNet"), which is a part of the city of San Francisco, CA, from approximately [N 37°46′43.39″, W 122°26′19.22″ (Golden Gate Avenue and Divisadero Street intersection)] to [N 37°46′51.78″, W 122°25′13.27″ (Golden Gate Avenue and Van Ness Avenue intersection)] and from [N 37°47′32.57″, W 122°26′28.90″ (Divisadero Street and Pacific Avenue intersection)] to [N 37°47′41.39″, W 122°25′23.71″ (Van Ness Avenue and Pacific Avenue intersection)] (see Fig. 5) is reported in [21] to study how various routing algorithms perform in a real network. Here, we summarize a test setting in SFNet and a part of the result that helps us to better understand the performances of routing algorithms in WOBAN.

SFNet is approximately a 1 mi^2 area in downtown San Francisco with an estimated population of around 15 000 residents.[1] The wireless part of SFNet is a mesh that consists of a number of P2P or P2MP routers.[2]

[1]San Francisco has an area of nearly 47 mi^2 with a population of around 745 000; therefore, the population of SFNet in Fig. 5 is quite representative of San Francisco's population density.

[2]In grayscale image (of Fig. 5), black squares (five of them) are attached to the optical part of WOBAN as gateways; others (20 of them) are routers.

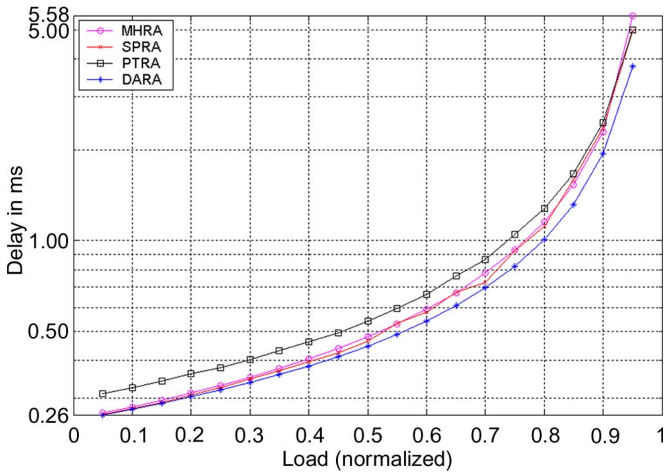

Fig. 6. Average packet delay versus load in SFNet.

SFNet is envisioned as a part of an on-going effort to deploy the San Francisco municipal network. SFNet contains 25 wireless routers in 1 mi^2 area, while five of these 25 routers are designated as gateways to the optical back end of a WOBAN and placed at the edges of SFNet.

We review a test result which captures one of our performance metrics (delay) for various routing algorithms in the SFNet WOBAN in Fig. 6. Fig. 6 shows that DARA outperforms MHRA, SPRA, and PTRA with respect to average system delay. More detailed numerical examples of various performance metrics can be found in [21].

V. Fault Tolerance: Risk Awareness in WOBAN

The network architecture of a WOBAN has an important characteristic of risk awareness. It can combat network failures by healing itself quickly. In the following, we review the fault-tolerant aspects of a WOBAN.

Failures in WOBAN (and, consequently, the loss of packets) may occur due to multiple reasons, viz. 1) wireless router/gateway failure; 2) ONU failure; and 3) OLT failure. Failures may also occur due to fiber cut, which results in the failure of gateways (if a fiber between an ONU and a gateway gets cut), ONUs (if a fiber between a splitter and an ONU is cut), and OLTs (if a fiber between an OLT and a splitter is cut).

The fault-tolerant property of a WOBAN may handle most of these failure scenarios efficiently. If a gateway fails, then the traffic can be redirected to other nearby gateways. Similarly, if an ONU fails, and as a consequence, one or multiple gateways fail, the packets will be rerouted to other "live" gateways that are connected to a "live" ONU. An OLT failure (and as a consequence, the failure of all ONUs connected to that OLT) is the most severe. In this case, packets from a large portion of the WOBAN will need to be rerouted.

Thus, to tackle these problems, a "Risk-and-Delay-Aware Routing Algorithm (RADAR)," which is an extension to DARA, has been developed (the details of which can be found in [22]). RADAR can handle the multiple-failure scenarios. RADAR differentiates each gateway in the WOBAN by maintaining a hierarchical risk group that shows to which PON group (ONU and OLT) a gateway is connected. Each

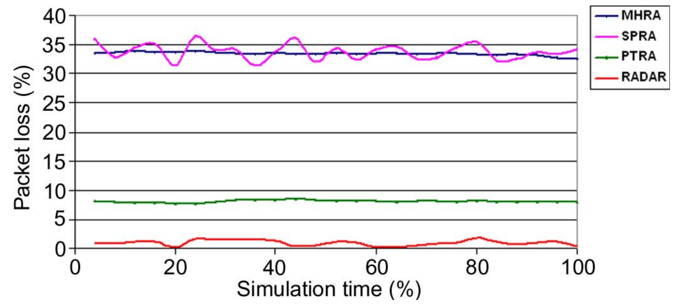

Fig. 7. Packet loss for ONU failure in SFNet.

gateway is indexed, which contains its predecessors (ONU and OLT indexes as well) to maintain the treelike hierarchy of a WOBAN. ONUs and OLTs are indexed in similar fashion. To reduce packet loss, each router maintains a "Risk List (RL)" to keep track of failures. In the no-failure situation, all the paths are marked "live." Once a failure occurs, RL will be updated and paths that lead to the failed gateway(s) will be marked "stale." Thus, while forwarding packets, the router will only choose a "live" path. The pros and cons of RADAR are captured in Table IV.

We review a result that captures the essence of risk awareness (and, consequently, minimizing the packet loss) of various algorithms in WOBAN in Fig. 7 in a test setting of SFNet (for more results, the reader is referred to [22]).

VI. Summary

In this paper, we reviewed an architecture and a vision for the WOBAN and articulated why the combination of wireless and optical presents a compelling solution that optimizes the best of both worlds. While this discussion briefly touched upon the business drivers, the main arguments focused on design and deployment considerations.

We discussed network setup, network connectivity, and fault-tolerant characteristics of the WOBAN. In the network setup, we reviewed the design of a WOBAN, where the back end is a wired optical network, the front end is configured by wireless connectivity, and in between, the tail ends of the optical part [known as ONUs] communicate directly with the wireless BSs (known as "gateway routers"). We summarized algorithms to optimize the placement of ONUs in a WOBAN deployment scenario. We also evaluated the pros and cons of the various routing algorithms (network connectivity) in a WOBAN, including its fault-tolerant characteristics, and presented some novel concepts that are better suited for such hybrid networks.

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