Hybrid Wireless-Optical Broadband Access Network (WOBAN): Prototype Development and Research Challenges

Pulak Chowdhury, Suman Sarkar, Glen Kramer, Sudhir Dixit, and Biswanath Mukherjee

Abstract—Hybrid wireless-optical broadband access network (WOBAN) is emerging as a promising technology to provide economical and scalable broadband Internet access. In this cross-domain network architecture, end-users receive broadband services through a wireless mesh front-end which is connected to the optical backhaul via gateway nodes. In this article, we present the architecture and functional characteristics of a WOBAN prototype built in the Networks Lab at UC Davis. We cite some research challenges on hybrid networks based on our experimental observations.

Index Terms—WOBAN, Prototype, Hybrid, Cross-Domain, Optical-Wireless.

INTRODUCTION

During the past decade, the backbone network has experienced enormous growth in capacity and reliability, mainly due to major development efforts in the area of optical networking. During the same time, bandwidth demands of technology-savvy end users for broadband services such as “quad-play” (voice, video, Internet, and wireless) and media-rich applications have also increased at an unprecedented rate. However, the access network (commonly referred to as the “last-mile” network) still remains a bottleneck for providing bandwidth-intensive services to customers. Legacy access technologies (such as Digital Subscriber Line (DSL) and Cable Modem (CM)) will not be able to carry the high volume of traffic generated by emerging applications such as video-on-demand (VoD), interactive gaming, or duplex video-conferencing. Thus, future access technologies should provide high capacity and operational efficiencies along with mobility support and untethered access to users in a cost-effective manner.

Optical-fiber-based technologies (e.g., fiber-to-the-home (FTTH), fiber-to-the-building (FTTB), fiber-to-the-curb (FTTC)) are well suited to support integrated high-bandwidth digital services, and can alleviate bandwidth bottlenecks. The next generation of access networks is therefore promising to deploy optical fiber all the way to the customer premises. However, laying fiber infrastructure to all end-users incurs significant cost. Furthermore, users also desire untethered access, especially if they are mobile. Wireless technologies can support mobility and untethered access. Unfortunately, wireless access is constrained due to limited bandwidth. Therefore, combining the complementary features of these two technologies (optical and wireless) can potentially provide ubiquitous (“anytime-anywhere”) broadband access to satisfy future customer demands. Therefore, a novel cross-domain network paradigm – Wireless-Optical Broadband Access Network (WOBAN) – which is an optimal combination of high-capacity optical backhaul and untethered wireless access, is proposed in the literature [1].

WOBAN shows excellent promise for future access networks. This cross-domain network architecture consists of an optical backhaul (e.g., a Passive Optical Network (PON)) and wireless access in the front-end (e.g., WiFi and/or WiMAX). In WOBAN, a PON segment starts from the telecom Central Office (CO) with an Optical Line Terminal (OLT) at its head end. Each OLT can drive several Optical Network Units (ONU), and each ONU can support several wireless routers of the wireless front-end in WOBAN. The wireless routers directly connected to the ONUs are called as wireless gateways. The wireless front-end also consists of other wireless routers to provide end-user connectivity. Therefore, the front-end of a WOBAN is effectively a multi-hop Wireless Mesh Network (WMN) which is connected to the high-capacity PON segment in the back-end, creating a cross-domain integrated network architecture.

There is another related architecture, known as Radio-Over-Fiber (ROF), where radio signals can be effectively carried over an existing optical fiber infrastructure using “Hybrid Fiber Radio” (HFR) technology [2]. ROF deals with the communication challenges of sending radio signals over fiber whereas WOBAN focuses on the networking aspects of the wireless-optical converged architecture.

In this article, we present the experiences gathered during a WOBAN prototype development, and discuss future research issues to improve the performance and design of this hybrid network. We provide detailed prototype development procedures and introduce some of the challenges involved in the development. The WOBAN prototype serves as the experimental setup for various access network protocols and data dissemination techniques; and it features programmability, resource sharing, and slice-based experimentation. We believe that this prototyping effort will lead us to identify and address several practical concerns that WOBAN may encounter in future.

The remainder of this article is organized as follows. We first present related prototyping efforts on hybrid cross-domain networks in the literature. We then present the WOBAN prototype architecture, its distinguishing features, and its development procedure. Experimental
results are demonstrated and discussed in the following section. Then, we elaborate on future research challenges of WOBAN. Finally, concluding remarks are provided.

**RELATED DEVELOPMENT EFFORTS**

This section briefly reviews other testbeds/prototypes developed for hybrid wireless-optical networks research.

Hu et al. [3] have developed a testbed for an Optical-Wireless Integration (OWI) infrastructure. They implemented SONET/WDM, popular in core optical networks, for the optical part and WiMAX (IEEE 802.16) for broadband wireless access. The edge node between two networks interfaces the WiMAX base station and SONET with a direct conversion between the protocol stacks of the optical and wireless segments.

Grid Reconfigurable Optical and Wireless Network (GROW-Net) [4] is another hybrid wireless-optical network which consists of an “Infrastructure” based WMN in the front-end and a reconfigurable, high-capacity, point-to-multipoint PON optical backhaul. To demonstrate the performance of the proposed optical backbone reconfiguration scheme in GROW-Net, the authors of [4] developed only an optical experimental testbed based on commercially-available devices. This testbed is dedicated to optical backhaul reconfiguration experiments.

Jia et al. [5] have developed a testbed for Radio-Over-Fiber (ROF) experiments. The testbed has two segments – (a) Central Station (CS) and (b) Base Station (BS) – and it consists of optical transmission equipments. The main purpose of this testbed is to illustrate how wireless signals can be carried over fiber. This testbed demonstrates the feasibility of a full-duplex ROF system based on optical carrier suppression and reuse for future optical/wireless networks.

**IMPLEMENTING WOBAN Prototype**

In this section, we discuss the logistics (resources needed for prototype development), WOBAN architecture, features, and detailed development procedure.

**Resources Needed**

Table I summarizes various device specifications used in our prototype. All these devices are commercially available off-the-self devices and can be used effectively to build a fully-functional and reasonable-sized prototype.

We use open source firmware OpenWRT\(^1\) to develop the reconfigurable wireless routers and gateways.

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**TABLE I**

**WOBAN Prototype Components and Their Specifications.**

<table>
<thead>
<tr>
<th>Components</th>
<th>Interface/Port</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLT</td>
<td>• Client Side: One EPON port</td>
</tr>
<tr>
<td></td>
<td>• Network Side: One 100/1000 Base-T Ethernet port (for RoI (Rest-of-the-Internet))</td>
</tr>
<tr>
<td>ONU</td>
<td>• Client Side: Two 10/100 Base-T Ethernet ports (to drive 802.11g routers)</td>
</tr>
<tr>
<td></td>
<td>• Network Side: One EPON port (to connect OLT)</td>
</tr>
<tr>
<td>Optical Splitter</td>
<td>1:8 power splitter</td>
</tr>
<tr>
<td>802.11g Router</td>
<td>• Client Side: One radio port</td>
</tr>
<tr>
<td></td>
<td>• Network Side: 10/100 Base-T Ethernet port</td>
</tr>
<tr>
<td>Clients</td>
<td>Laptops, PDAs, etc.</td>
</tr>
</tbody>
</table>

**Architecture**

Figure 1 shows the architecture of WOBAN prototype developed in the Networks Research Laboratory at UC Davis.

The wireless routers form the WOBAN front-end and connect to the end users (who can be scattered over the geographic area served by the WOBAN and who are not shown in Fig. 1). These wireless routers (IEEE 802.11g) support data rates up to 54 Mbps. Several designated routers are configured to have Gateway capabilities (by loading appropriate open source firmware) and each such Gateway is connected to an ONU via a 10/100 Base-T Ethernet port. The wireless routers are placed with an effective distance of 50-60 meter between pairs.

Two OLTs (Optical Line Terminal) emulate the functionality of the telecom Central Office (CO) of the general WOBAN architecture. Each OLT can drive several ONUs using an optical splitter. The OLTs and ONUs are connected through Ethernet PON (EPON) ports. The OLTs are connected to the Rest of the Internet (ROI) using the campus-wide backbone network at UC Davis.

The prototype architecture is divided into three planes: (a) Control Plane, (b) Data Plane, and (c) Management Plane. The Control Plane is used to define different control features of the nodes in the WOBAN prototype. The Data Plane configures routing and different data-transfer scenarios, and collects measurement data for different experiments. The Management Plane is used for remote access and programmability of the prototype nodes. The WOBAN Network Operations Center (NOC) (see Fig. 1) is responsible for the management of all these planes.

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Distinguishing Features

The WOBAN prototype has several distinguishing features which are different from other related prototypes ([3], [4], [5]) reported in the literature, as follows.

- To the best of our knowledge, this is the most integrated wireless-optical hybrid network testbed. Other testbeds have only a small number of nodes and have been used as proof of concepts. On the other hand, WOBAN prototype features programmability, self-organization, and slice-based experimentation.
- The WOBAN prototype is large enough to demonstrate its useful properties, e.g., two OLTs can demonstrate fault-tolerance properties of WOBAN so that, if one OLT breaks, the other parts of the WOBAN can “self organize” themselves to still carry the affected traffic through the other operational parts of the WOBAN. The self-organization property of WOBAN also holds for (1) other failure types, e.g., ONU failure, fiber cut, wireless router failure, etc. and (2) optimal routing.
- The deployment and management cost of WOBAN prototype is low as it is built from highly-customized off-the-shelf components, open sources, and indigenous software.
- The front-end can be set up as a plug-and-play wireless mesh.
- The prototype nodes feature programmability. The open source firmware provides the programmability in the wireless routers. The programmability of OLT can be performed by using the craft port in the OLT box and the ONU programmability can be emulated by gluing a separate “Linux box” with each ONU.
- The prototype is reconfigurable and provides self-organizing and self-healing properties. The reconfigurability is performed by Layer-2 (L2) connectivity and intelligent routing.
- Power consumption of the wireless nodes is very low (1-2.5 watts/router). As the wireless mesh constitutes a large part of the prototype, the overall power consumption is also low.

Development Procedure

Here, we present deployment issues related to different planes in the WOBAN prototype and show how they are addressed during the deployment phase.

Control-Plane Issues:

- Topology Creation/Connectivity: The optical segment of the WOBAN prototype has a static topology initially as connections between nodes are wired. The wireless segment uses proactive routing (namely Optimal Link State Routing (OLSR) in our prototype) to create a “self organizing” topology where, in case of a router failure, nodes can redirect traffic to the nearby active routers. If a failure occurs in the optical segment, dynamic protection scheme can be applied for “self-healing”.
- Dynamic Bandwidth Allocation (DBA): The optical part of the WOBAN prototype uses Ethernet PON (EPON) as the basic technology. In EPON,
the Ethernet functionality is emulated by a Layer-2 signalling mechanism, called Multi-Point Control Protocol (MPCP) [6] that would allow the OLT to assign the bandwidth dynamically among ONUs. We can use hierarchical MPCP-based protocol in two levels (OLT-to-ONUs and ONU-to-Gateways) coupled with Layer-2 signaling (Gateways-to-Routers) for DBA, and thereby achieve stronger wireless-optical integration. Overview of this kind of protocol is given in a later section.

- **Programmability**: An important aspect of the WOBAN prototype nodes is their programmability. Experimental testbed researchers should be able to create, modify, and test their protocols on the prototype. In our WOBAN prototype, we create a simple remote-access-based programmability platform for the wireless nodes (gateways/routers). This platform provides programmability at each layer of the IEEE 802.11 protocol stack. The OLT DBA mechanism (Layer-2 signalling) can also be programmed using the craft port installed in the OLT box. For ONU, we can emulate the programmability by gluing a “Linux box” with each of them.

**Data-Plane Issues:**

- **Routing**: Proactive routing such as Optimal Link State Routing (OLSR) is used in the wireless mesh and Layer-2 static routing is used in the optical part of the WOBAN prototype. Dynamic routing protocols such as OLSR waste significant amount of wireless bandwidth for periodic link-state updates. From our prototype experience, we find that static routing can perform better compared to a dynamic approach in a WOBAN-type network architecture. One such proposal is discussed below.

- **Configurations**: Prototype nodes can be configured for different experiments. These data-transfer configurations facilitate us to obtain experimental data for various applications on the WOBAN prototype.

- **Measurement**: Network protocol analyzers (e.g., tcpdump, Wireshark\(^2\), etc.) are used to collect and analyze network statistics from various experiments.

**Management-Plane Issues:**

- **Remote Access**: In the WOBAN prototype, we use remote access interfaces to download our own code inside the nodes and run the experiments. Wireless nodes are connected with the NOC through wireless interfaces, and optical nodes are connected through craft ports.

- **Network Slicing**: To share the WOBAN testbed resources among several experiments, currently physical slicing is used. In physical slicing, resources are physically divided among different experiments.


We can also implement the virtual slicing feature where the physical resources of WOBAN nodes can be shared among experiments. Time-Division Multiplexing (TDM) based virtual slicing is very challenging to implement [7]. Further research is required to deploy such features in the prototype.

**EXPERIMENTAL ILLUSTRATIONS**

Here, we present experimental results collected from the WOBAN prototype for various applications (Data, Voice-over-IP (VoIP), and Video-on-Demand (VoD)).

**Experimental Setup**

Figure 2 shows the setup for different experiments on the WOBAN prototype. The wireless front-end of WOBAN should have distributed control to exhibit self-healing and self-organization properties. Therefore, we use IEEE 802.11 basic Distributed Coordination Function (DCF) for medium sharing. IEEE 802.11 Point Coordination Function (PCF) is only suitable in wireless “infrastructure” mode, hence is not feasible for WOBAN wireless mesh front-end. IEEE 802.11e-based enhanced coordination functions for better QoS performance have not been considered in our experiments as this standard is relatively new and is still in the development phase. Transmission rate of wireless routers is set to 54 Mbps.

In all the experiments, background traffic load is generated using software-based traffic generators. We run our experiments under no background load to heavy background load to find out the effects of background traffic on different applications. In all the experimental setups, one end (server/client) of a connection is located in the RoI, and the other end (wireless client) is connected to the wireless mesh through multiple hops. Background traffic also flows between these two ends so that all the links of a experimental connection experience some external traffic load.

The quality of the wireless channels varies randomly across the experiments due to different interference factors in our environment. This inherent randomness of wireless channels may have impacts on accumulated results. The impact of wireless channel quality on the performance is not studied in these experiments. We mainly focus on various applications’ performance under random wireless environments. Our results indicate that, as the number of wireless hops increases, various performance quality measures decrease, due to bottleneck in the wireless mesh. Therefore, our accumulated results present the performance of different applications by varying the number of wireless hops.
Results

Data: We start with data-transfer applications such as secure file transfer (viz., sftp or winscp). In our experiments, transferred file size is 76 MBytes. Figure 3 shows the data-transfer application’s end-to-end throughput. As expected, with increasing number of wireless hops, end-to-end throughput decreases significantly. Furthermore, presence of background traffic decreases the throughput.

Voice-over-IP (VoIP): Next, we present the VoIP end-to-end performance. We use skype as the VoIP application. Figure 4 presents different performance measures for skype-based experiments. As the number of wireless hops increases, both packet-loss rate and jitter increase, resulting in degraded voice quality. Voice quality also degrades with the increase of background traffic load. We use the performance metric of Mean Opinion Score (MOS) [8] to measure the subjective voice quality. MOS gives a numerical indication of the perceived voice quality. MOS is expressed in one number, from 1 to 5 after experiencing the voice quality in different experiments. Then, the mean is calculated to determine the MOS for different experimental setups. By comparing the VoIP performance measures, it is evident that packet-loss rate increases (hence voice quality (or MOS) decreases) with the number of wireless hops. As expected, too many wireless hops will not help to improve the WOBAN performance.

Video-on-Demand (VoD): Performance measures for video transmission are presented in Fig. 5. We use Darwin Streaming Server\(^3\) as VoD server and VLC Player\(^4\) as client for our video experiments. In this real-time video streaming scenario, the VoD server broadcasts the video and the client plays the broadcasted streaming video. The broadcasted streaming video file is 30 sec. in duration, \(640 \times 480\) pixels in size, and encoded at 500 kbps. Figures 5(a) and 5(b) show the corresponding packet-loss rate and jitter, respectively, with number of wireless hops. Figures 5(c)-5(f) (screen shots taken at 17 sec. of the video streaming on the client side) show the qualitative video streaming performance with different number of wireless hops. In these figures, the background traffic is assumed to be moderate (1.5 Mbps). As the number of wireless hops increases and as expected, the video packet-

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loss rate increases, and the video quality deteriorates. Till two wireless hops, we can receive decent quality of video. After three hops, the video is blurred (Fig. 5(f)), and after four hops only a blank screen shows up in the video client. A heavily-congested network also significantly affects the quality of video transmission. Therefore, the wireless mesh front-end of the WOBAN should not have many wireless hops if it has to provide quality broadband services to end users.

**Critical Observations**

We accumulate the following observations from our WOBAN prototyping procedure and experiments.

- Many wireless hops do not help. But intelligent Gateway placement in the wireless mesh may help to reduce the number of wireless hops, and improve the overall WOBAN performance. We can also put more Gateways in the mesh to decrease the number of wireless hops.
- Intelligent channel assignment in the wireless mesh can help to improve performance. We found that, during our mesh setup, if channel 1 of the 2.4-GHz band is assigned to the wireless routers, we can get better results compared to assigning channel 6. This is due to several other interfering routers (outside of our WOBAN) near the mesh setup working on
channel 6. All the results presented in this article have been collected using channel 1.

- A dynamic link-state routing protocol such as OLSR wastes a lot of wireless bandwidth. As the WOBAN front-end is a relatively static mesh and a small number of wireless hops is needed for improved performance, the WOBAN mesh performance can be improved by using static routing.
- Wireless nodes near a Gateway carry more traffic compared to distant ones. Therefore, the memory and processing power of these “closer” nodes should be higher. Moreover, from prototyping viewpoint, current processing power and memory of off-the-shelf wireless routers will not be sufficient for virtual slicing (where several experiments are running on the same physical resources).
- As the optical segment of the WOBAN prototype uses a TDM-based Medium Access Control (MAC) scheme, for better wireless and optical integration and for improved performance, a TDM-based MAC would be a better choice for the wireless mesh.
- For video transmission, the standard MAC protocol is not sufficient. The MAC layer should be able to distinguish and prioritize between video frames and other traffic for better video performance.
- Although a wireless node can have a theoretical maximum capacity of 54 Mbps, due to interference and other surrounding interference, the wireless capacity achieved is very low.
- Routing in the wireless mesh without considering the optical segment’s traffic condition does not help, and vice versa. Therefore, an integrated routing approach will help to improve WOBAN performance.

**Research Challenges**

In this section, we discuss some research challenges which we have accumulated from the experience gathered from our WOBAN prototype development.

*Layer-2 Integrated Routing*

Current deployment of WOBAN assumes separate data-transfer techniques for optical and wireless segments. In the optical part, we use MPCP-based Dynamic Bandwidth Allocation (DBA), whereas the wireless mesh uses Layer-3 routing, namely OLSR. So, current WOBAN deployment employs a loosely-integrated network architecture and control. Layer-3 routing in the wireless mesh also poses significant overhead on the network. To provide seamless integration of the optical and wireless segments, and to reduce Layer-3 processing overheads, an interesting alternative is an integrated Layer-2 (L2) routing protocol which can efficiently route traffic through all segments of WOBAN.

The optical segment of WOBAN already uses MPCP-based DBA, namely Interleaved Polling with Adaptive Cycle Time (IPACT) [9]. Therefore, one can develop a hierarchical MPCP-based L2 routing for WOBAN (multi-point control for an OLT to its downstream ONUs and for an ONU to its downstream Gateways). The idea of L2 routing can be extended in the optical segment (till the Gateways) so that it fits with the wireless mesh architecture with one ONU driving multiple Gateways (similar to the case where one OLT drives multiple ONUs). The wireless mesh will use a spanning tree for L2 routing. This approach is consistent with the idea of end-to-end L2 capability of WOBAN.

*TDM MAC for Wireless*

Traditional wireless mesh uses collision-based MAC protocols. Our current deployment based on IEEE 802.11g wireless routers uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC protocol. From our testbed experience, it is evident that CSMA/CA poses a hindrance on the limited wireless capacity. From the literature, we find that a TDM-based MAC protocol can improve the capacity of the wireless mesh. Furthermore, as we envisioned for a L2 routing approach earlier, a TDM-based MAC will also be consistent with a L2 routing protocol. Therefore, a TDM-based MAC protocol for the wireless mesh will lead to the seamless integration of both optical and wireless segments of WOBAN. Other MAC protocols like Orthogonal Frequency Division Multiplexing (OFDM) combined with TDM can also be considered in the future to improve wireless capacity.

*Improve Flexibility in WOBAN Architecture*

Existing PON technologies do not exhibit sufficient fault tolerance and self-organization capabilities. In case of OLT, ONU, or wireless gateway failures in a WOBAN, we need to redirect the traffic to other live nodes. The self-organization and fault-tolerant properties of WOBAN should ensure this flexibility. Moreover, when an ONU gets congested due to heavy load, we need to perform load shifting and load balancing so that the network’s health is ensured.

*Hierarchical Architecture*

From our experimental observations, it is clear that wireless Gateways and routers near a Gateway carry more traffic compared to routers which are far away from a Gateway. Therefore, the routers in the vicinity of the Gateway and the Gateway itself should be well-equipped with high-capacity wireless resources. The capacity of wireless routers can be increased using technologies such as multiple radios, directional antenna, and Multiple Input Multiple Output (MIMO), etc.
CONCLUSION

In this article, we showed how to build a prototype for a novel, high-bandwidth future access network technology, named WOBAN. This technology is envisioned to satisfy future bandwidth demand of technology-savvy customers in a cost-effective manner, and it can be an attractive solution for future “last-mile” access networks. We demonstrated the performance of several typical applications such as data transfer, voice, and video over our WOBAN prototype. We observed that too many wireless hops degrade the application performance, particularly for video. Future research challenges accumulated from our prototyping experiences were also illustrated. The WOBAN prototype will be instrumental to develop, test, and analyze the performance of hybrid network protocols. This programmable and configurable access architecture will facilitate future experimental, hybrid, and cross-domain networking research.

REFERENCES