GROW-Net – A New Hybrid Optical Wireless Access Network Architecture

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Abstract

— We propose a novel hybrid optical wireless access network architecture that is designed for highly populated metropolitan area. This hybrid access network consists of an optical grid network providing broadband backhauling, and many wireless mesh networks penetrating into the neighborhoods to provide low cost, ubiquitous links. This hybrid access network architecture is scalable and flexible enough to easily meet varying demands for bandwidth of end users: As bandwidth demand increases, the capacity of the hybrid access network can be upgraded by deploying more access points in the wireless mesh network until its performance begins to degrade due to high hop-counts. As the performance degrade occurs, additional fiber are deployed (or dark fibers activated) to enhance the overall network capacity. On the optical grid backhauling network, we propose a hierarchical loop routing protocol to enhance the routing efficiency. Intra-cell hybrid adaptive routing protocols and algorithms are proposed to achieve the optimum network performance provided by this hybrid access network.

Keywords – hybrid access networks, wireless mesh network, hierarchical loop routing protocol, intra-cell hybrid adaptive routing protocol and algorithm.

1. INTRODUCTION

Over the past several years Internet traffic has been growing by nearly 100% a year. This excessive growth in Internet traffic has strained the existing telecommunication infrastructure, especially the access network, which connects end users to a central office (CO). Recently, a significant amount of researches has been done on how to provide cost-effective broadband connections to the end-users in access networks. Today access technologies can be categorized into: (a) Copper-wire based technology such as Digital Subscriber Loop (DSL) or Hybrid Fiber Coax (HFC); (b) Optical access networks such as Passive Optical Network (PON); and (c) Wireless access networks such as WiMax. In a highly populated and dense metropolitan area, however, the ever-increasing demand for higher bandwidth and the need for large-scale deployment make existing solutions based on single access technology more and more impractical in providing a broadband and ubiquitous access connections to the end users. Therefore, in this paper we propose a novel _hybrid optical wireless access network architecture_ that combines the advantages of both types of network – the high capacity provisioned by optical networks, and the flexibility and cost-effectiveness provisioned by wireless mesh network. We name it "GROW-Net", which stands for **G**rid **R**econfigurable **O**ptical **W**ireless **Net**work.

GROW-Net is designed to provide broadband access connections in highly populated urban area. In its basic architecture, an optical reconfigurable grid network is deployed to provide highly scalable and broadband backhauling, while a wireless mesh network is deployed in the user's neighborhood to provide a cost-effective and ubiquitous links. By incrementally adding optical fibers and associated components to the optical grid network, the GROW-Net flexibly scales up to adapt to future increase in bandwidth demand.

This paper is organized as follows. In section 2 we provide background information about optical access and wireless mesh networks. In section 3, we describe and discuss the GROW-Net architecture. Section 4 summarizes the key attributes of the proposed network.

2. BACKGROUNDS

2.1 Optical Access Networks

Optical broadband access networks provide last-mile connectivity to the end users. Because of its passive nature and shared infrastructure, Passive Optical Networks (PONs) are considered cost-effective compared to active networks. Depending on the fiber penetration, PONs can reach the home (Fiber-to-the-Home, FTTH) or the curb (Fiber-to-the-Curb, FTTC) and could use vDSL over copper for end transmission to the home. Current standards, including Ethernet PON (EPON), Broadband PON (BPON) and Gigabit PON (GPON) are Time Division Multiplexing based, using one downstream and one upstream wavelength. Current research effort has been focused on the development of ultra-broadband Wavelength Division Multiplexing (WDM) PON of hybrid PON architecture for smooth migration from TDM to WDM system [1]. Even though PONs provide high capacity to the users, their deployment cost are relatively high.

2.2. Wireless mesh network

The IEEE 802.11 is a well developed and widely deployed Wireless Local Area Networks (WLAN). It operates in the unlicensed 2.4 and 5 GHz radio bands,

with an 11 or 54 Mbps data rate. Typically WLAN employs access points (APs) to provide access within a radius of up to 300 ft. Even though WLAN has been successfully bringing low-cost and flexible wireless link to users, its deployment is limited to local areas such as home and office where access to a wired infrastructure is available.

To extend this wireless link out of the local area, wireless mesh networks composed of WLAN APs have drawn a lot of attention [2]. As shown in Fig. 1, a wireless mesh network consists of multiple APs and mesh portal(s) connected to wired-infrastructure. Each APs in the mesh network deals with 2 types of links: 1. AP-User link that connects the AP and local users, as in conventional WLAN. 2). AP-AP link, which connects the mesh APs for routing traffic to/from the portals. Note that WLAN technology is highly desirable for the two types of link due to its cost-effectiveness and technology maturity. The routing protocol for the mesh network can be constructed on top of the PHY and MAC layers defined in WLAN [3].

In a wireless mesh network, a packet can usually be routed along multiple paths and each path consists of multiple hops. For example, in Fig. 1 the following 3 routes can be used for traffic route between AP0 and portal2: AP0-AP2-portal2 and AP0-AP5-portal2; both with two hops. To choose the optimum routing path, many routing algorithms [4] have been developed for wireless ad-hoc network. Thanks to the coverage extension enabled by wireless mesh networks, WLAN technology has been aggressively employed to serve end users in wider area. In San Francisco (US), for example, wireless mesh network will be deployed city-wide to provide access service. In this network architecture, wireless mesh network is laid as the bottom layer [5] and a large number of mesh APs will be deployed to penetrate into the neighborhood.

Even though wireless mesh network provides low-cost and flexible access connection, as the number of hops (hop-count) increases, wireless mesh network suffers from significant packet latency and loss, and it results in bandwidth/performance degradation [6]. To optimize the network performance experienced by the end users, therefore, the hop-count between AP and portal should be limited in certain way. A straightforward solution is to increase the number of portals so that the average hop-counts can be reduced [6].

3. GROW-NET ARCHITECTURE

In light of the high capacity and flexibility provided by optical and wireless mesh networks respectively, we believe that a hybrid access network combining advantages from the two heterogeneous networks is highly beneficial. We propose the Grid Reconfigurable Optical and Wireless Network (GROW-Net), which is a
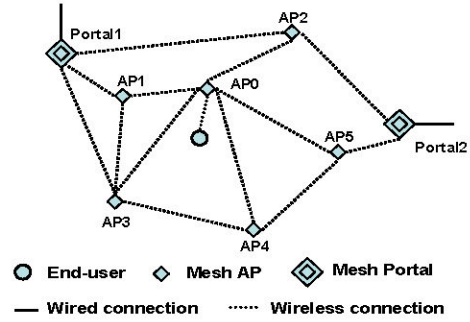

Fig.1. Wireless mesh network

hybrid access network designed for high population-density area.

As shown in Fig.2 (a), GROW-Net has an optical grid network dividing the urban area into grid cells, and each cell encloses a wireless mesh network, as shown in Fig. 2(b). In its basic architecture, the optical grid network enables high-capacity backhauling, and the wireless mesh network penetrates deeply into the neighborhood to provide a ubiquitous link. We will design a reconfigurable optical grid node and deploy it at fiber intersections to enable dynamic wavelength routing and add/drop operations. Wireless mesh portals are connected to the reconfigurable grid nodes through optical fiber. Along the grid cell, wireless traffic is collected/distributed from/to mesh portals by the Hybrid Cell Manager (HCM), which manages multiple grid cells in its proximity. For example, in Fig. 2(b) the HCM manages four grid cells. To route the traffic between any HCM and the CO on the metro ring network, a novel hierarchical loop routing protocol (sec 3.2) is proposed to facilitate efficient traffic routing on the optical grid network.

3.1. Architecture scalability and flexibility

To study GROW-Net's scalability and flexibility, we define the "average demand-density" as the total bandwidth demand divided by the total area (Gbps/km^2) in an area. Then we find the "sweet spot" boundary between optical and wireless transport according to the demand density.

As shown in Fig. 3, depending on the demand-density, GROW Net virtually and flexibly shift the "sweet spot" from the CO to the end-user as demand density increases. When demand-density is low (top case), the "sweet spot" should be set close to the CO, i.e. wireless link should occupy a large portion of the connection between the CO and end-user to achieve a cost-effective access link. This case is reflected by the large grid cell, in which wireless mesh network takes care of users in a wide area. As demand-density increases, we can increase the AP and portal density within the mesh network to enhance the capacity, until the wireless network performance or bandwidth efficiency degrades seriously due to large number of hop-counts. As the performance degrade occurs, the overall system capacity can be upgraded by adding new fibers (or activating dark fibers
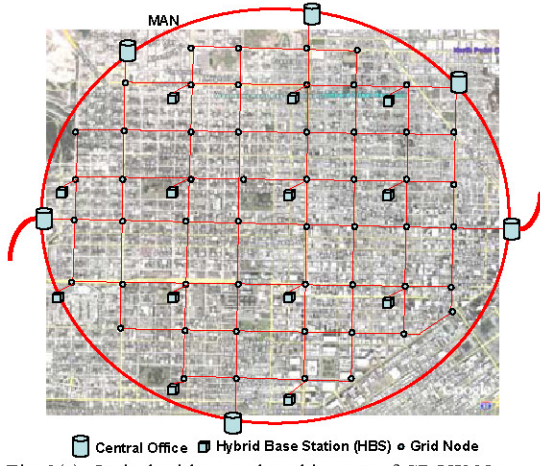
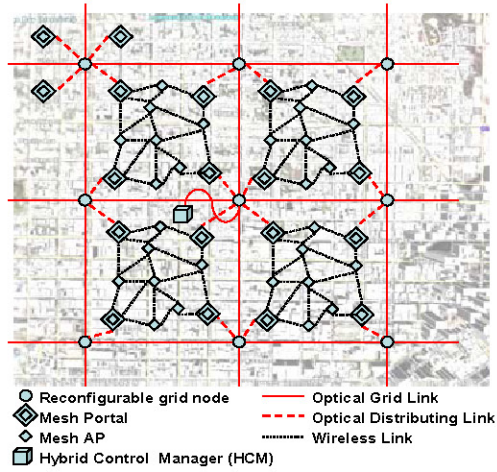Fig. 2(a). Optical grid network architecture of GROW-Net

Fig. 2(b). Wireless mesh network of GROW-Net

if available) to make a denser optical grid network. In this way the original grid cell is divided into several smaller cells, and the average number of APs in each grid is reduced. By adding new mesh portals in the gird cell, the resultant hop-counts in the wireless network will be reduced, and the potential bandwidth provisioning is upgraded.

3.2 Hierarchical loop routing on the optical grid

To route traffic efficiently on the optical grid network, a hierarchical HCM and loop routing protocol is proposed. Compared with conventional optical network, the proposed algorithm forms multiple WDM loops on the optical grid network. Forming WDM ring sub-networks on a mesh has been reported in [7]. In our proposed loop routing algorithm, however, arbitrary WDM loops are formed in a "hierarchical" way such that the traffic from any HCM can be routed through WDM loops on the entire grid network. The reconfigurable grid node at each fiber intersection enables the loops to dynamically balance traffic loads or recover service upon fiber link failures.

The logical hierarchical HCM architecture is illustrated in Fig. 4(a), where the HCMs are categorized into different levels. The 1st-level HCM is deployed in the
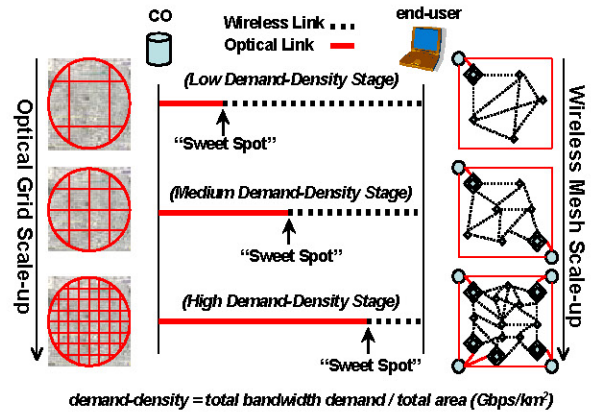

Fig. 3. GROW-Net enables flexible shifting of "sweet spot" between CO and end users.

largest number throughout the optical grid network. Each 1st-level HCM manages its 4 neighbor grid cells. The 2nd-level HCM, in addition to its 4 neighbor grid cells, will also manage its 4 proximal 1st-level HCMs, i.e. collect/distribute the traffic from/to the 1st-level HCM. Note that in the hierarchical HCM structure the connection at higher level will require higher capacity because of the aggregated traffic. The HCMs of different levels are interconnected by WDM loops with different capacities, as shown in Fig. 4(b) with the thickness of each loop line represents its capacity. HCMs at higher level are interconnected by loops with more capacity. The loop capacity is proportional to the number of optical WDM channels (λ's) used to carry traffic. To utilize λ's efficiently, the optical channels will be reused throughout the entire optical grid network. For example, in Fig. 4(b) λ_1 and λ_2 are reused throughout the grid network for the 1st-level HCM to collect/distribute traffic. Fast tunable lasers will be employed in the HCMs to facilitate resource sharing.

3.3. Intra-cell hybrid adaptive routing protocol and algorithm

In GROW-Net a grid cell and its enclosed wireless mesh network can have multiple mesh portals with different bandwidths. Mesh networks with portals typically employ shortest-path or spanning-tree routing algorithms [8]. These algorithms do not always provide an efficient use of the wireless network and fail to consider the bandwidths supported by individual portal. For example, the closest mesh portal to a particular AP might not have the capacity required, or the tree root portal might be very far away from a given access point. For these inefficiency reasons, we propose a hybrid adaptive QoS-based routing algorithm that can make use of the capacity information of each mesh portal and route intra-mesh network packets according to these capacities, performing load-balancing when needed and optimizing the overall performance of the network. In addition, through wireless cross-layer optimizations, the performance of the mesh network can also be improved.
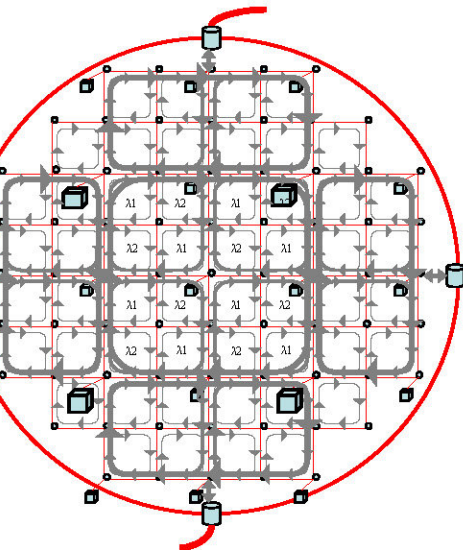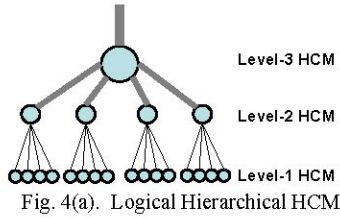
Fig. 4(a). Logical Hierarchical HCM

Fig. 4(b). Hierarchical HCM and Loop Routing

Fig. 5. Intra-Cell Hybrid Adaptive Routing

In AODV and other Ad Hoc network protocols [9], the information transmitted from one node to the next in the protocol messages usually reports only the number of hops to a particular destination. We intend to modify these protocols to include information regarding the capacity and QoS parameters of the nearest mesh portal. This extra information can be used for resource scheduling [10] and for QoS routing: through which of the mesh portals should the AP communicate with the exterior world and route its packets accordingly. This decision will be a tradeoff between the distance to a particular mesh portal and its capacity.

As an example, take the hybrid wireless/fiber-optic cell in Fig. 5. Suppose that AP x has a large amount of traffic queued and that portal B has a larger bandwidth available than any other portal. In this case, even though portals A and C are just two-hops away from x, it might be better for x to route its traffic through B. This decision is done locally at x, since it has information not only regarding the distance in hops to every MP, but also their available bandwidths.

By using the intra-cell routing algorithm described above, the multi-hop wireless mesh network adapts its traffic routing to the capacities provided by the optical grid cell through the mesh portals. In this case, the wireless network is adapting to the fiber optic network. Nonetheless this adaptation also takes place in the inverse direction: the fiber optic network adapts to the wireless network demands by knowing the utilization of each portal and number of hops to the final APs. By having both networks, the wir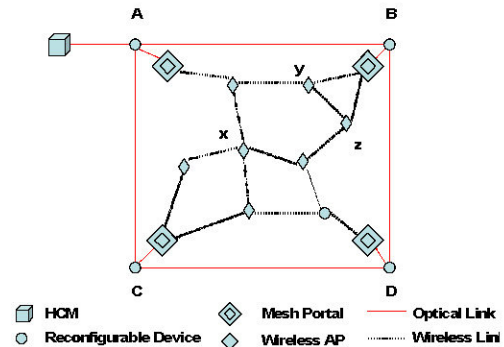eless mesh and the fiber optical grid cell simultaneously adapt to each other, the overall performance of the network is considerably improved, its utilization is much higher and it is more cost-effective.

4. CONCLUSION

In this paper we have proposed the GROW-Net, a novel hybrid optical wireless access network architecture. GROW-Net is designed to provide cost-effective broadband access connections in a highly populated and dense metropolitan area and consists of an optical grid network that provides a broadband backhauling, and IEEE 802.11-based wireless mesh networks that penetrate into users neighborhood to provide a low cost and ubiquitous link. Its architectural scalability and flexibility make the GROW-Net highly adaptive to the bandwidth demands in a cost-effective way. For traffic routing on the optical grid infrastructure, we propose a hierarchical loop routing protocol. In addition, since GROW-Net provisions multiple mesh portals within a grid cell, we propose to develop intra-cell hybrid adaptive routing protocols and algorithms to achieve optimal network performance experienced by the end users. Detailed implementations of the reconfigurable node and routing protocols are now under extensive study.

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