Grid Reconfigurable Optical-Wireless Architecture for Large Scale Municipal Mesh Access Network

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Abstract—This paper presents a novel hierarchical and grid based reconfigurable optical-wireless network (GROW-Net) architecture. GROW-Net supports scalable and flexible integration of a large scale wireless mesh network in a municipal environment. Under the GROW-Net architecture, a joint evolution strategy is proposed to allow graceful upgrades in both optical backbone and wireless mesh network. To alleviate the known throughput bottleneck in mesh networks, a capacity enhancing technique based on flexible cell-splitting is proposed. The technique allocates wavelength resources to unutilized dark fibers using the unique structure of GROW-Net’s reconfigurable and colorless access gateways. To analyze the effectiveness of the approach, throughput performance of the wireless mesh network is analyzed using a high fidelity simulator. The wireless mesh network in the simulation employs a distributed and cooperative medium access control protocol within a time division multiple access and time division duplex framework. Through the high fidelity simulation, results show the degree of throughput enhancement by using cell splitting method. The evolution strategy further enables the backbone to scale its bandwidth and adapt to future high throughput and very high throughput wireless technologies. The performance of the proposed backbone is demonstrated experimentally over the optical testbed.

Keywords—Wireless mesh network; optical access networks; integrated access gateway; cell splitting; throughput analysis.

I. INTRODUCTION

Multi-hop wireless access networks have gained significant interest in the past several years. Many cities actively consider deploying wireless mesh networks (WMNs) with infrastructure support to provide high-speed metropolitan area access network (MAN). Muni-WMN is considered to be an affordable solution to provide packet data communication across wide geographical areas. Despite these advantages, until to date Muni-WMN networks have limited performance due to their inability to deliver broadband-like experience to end users across a large area.

Optical networks can provide many complementary characteristics to wireless networks. The advent of optical access networks, such as time division multiplexed (TDM) based passive optical networks (PONs), can provide the cost-effective, scalable, and robust backhaul solution to local wireless access or home networks. However, to support the high dynamicity of aggregation traffic and wide geographical coverage presented in large scale wireless access networks, a new architecture must be considered to sufficiently address problems under the constraints of municipal environments.

This paper presents the grid reconfigurable optical-wireless network (GROW-Net) architecture. GROW-Net is a grid based network that utilizes fiber resource more efficiently than currently known approaches in the municipal area. The hierarchical and integrated architecture of GROW-Net allows efficient network management and sharing among the wireless and optical segments. This paper further illustrates a novel joint evolution strategy that bridges the gap between the vision and the reality in the “broadband everywhere” notion.

The outline of the paper is organized as the following. The paper first reviews related works in optical-wireless access network integration for MANs. In section III, it introduces the GROW-Net hierarchy. In the WMN segment, the network employs a novel cooperative and distributed time division multiple access for time division duplex networks. The optical backbone network employs novel integrated technologies to support efficient traffic aggregation and flexible resource allocation. Section IV illustrates the joint evolution strategy that allows flexible addition of gateway drop points and adaptations to future enhanced wireless interfaces. The evolution strategy is possible under the GROW-Net architecture because it provides cost-effective fiber penetration and flexible resource allocation. Section V first presents the WMN throughput scalability observed in high-fidelity simulation. The high fidelity simulator accounts for wireless impairments and channel propagation properties specific for municipal areas. Then, the section demonstrates the proposed backbone network. Section VI presents the enabling technologies for the reconfigurable device used in the GROW-Net’s optical testbed. Finally, Section VII summarizes the paper.
II. RELATED WORKS

Traditionally, T1 and/or other leased lines are used to support wireless access backhaul. The leased lines solutions are not cost-effective nor can these copper-based circuits support the amount of bandwidth and dynamicity of traffic expected in next-generation wireless technologies. Recently, there were some preliminary works that utilized optical access networks as a backbone network to wireless access networks. Most of the attention in this area has gone to the integration between EPON and WiMAX because of their shared similarities. There have been a number of papers exploiting their similar gateway capacity and bandwidth request-grant mechanisms. EPON is typically viewed as an efficient backbone transport network to the WiMAX network. In [1], the authors demonstrated the EPON performance in transporting voice and data service over a combined WiMAX/EPON network. Traffic mapping and bandwidth allocation methods are exploited in [2]. There are also considerable amount of attention in incorporating radio-over-fiber (RoF) technology in EPON-WiMAX system to enhance capacity [3].

There has been also significant interest in integrating EPON and WiFi because of the ubiquity and cost-effectiveness of the latter technology. The WOBAN [4] architecture integrates WiFi with existing EPON infrastructure and investigates a delay-aware routing technique to support alternative routing during ONU failure. The MARIN [5] architecture proposes a metropolitan area architecture that consolidates multiple EPON distribution networks into a unified coarse wavelength division multiplexing (CWDM) ring network. MARIN supports mesh networking and proposes an integrated load-balanced routing technique and enhances capacity by exploiting alternative paths in multi-hop routing.

GROW-Net proposes a new architecture that incorporates evolutions in both wireless and optical segments. The architecture presents a novel method to flexibly bring fiber deeper into the municipal areas. This architecture employs a cost-effective, reconfigurable and reflective technology to bring realistic broadband experience to end users. This paper examines the throughput bottleneck in current wireless mesh networks and utilizes a joint evolution strategy to alleviate the bottleneck issue.

III. GROW-NET HYBRID ARCHITECTURE

GROW-Net is based on a hierarchical network design that employs a wireless mesh access network segment and an optical backbone network segment. Figure 1 illustrates the GROW-Net hierarchy. In the wireless mesh network, access gateways (AGs) connect to the fiber backbone and provide the point of ingress and egress traffic for aggregated downstream and upstream traffic, respectively. The access routers (ARs) serve as the intermediate node and relay transit traffic before they arrive to the destination. The end users (EUs) are connected directly to their nearest access routers. There are three types of wireless connections: gateway-router, router-router, router-end user. In GROW-Net, all three wireless connections initially employ the same air interface, as it is in a homogeneous 802.11x network. The optical backbone network also employs a three-layer hierarchy that consists of a metropolitan point of presence (POP), multiple aggregation terminals (ATs), and AGs that connect the optical network to the WMN. The aggregation terminals, or equivalently the optical line terminals (OLTs) in EPON, aggregate local loop traffic and transparently transports it over the metropolitan backbone toward the POP.

A. Large scale wireless mesh network

1) PHY and MAC:

We consider a time division multiple access (TDMA) and time division duplex (TDD)-based framework. Fig. 2 shows the frame structure of the wireless mesh network. There are two types of time slots: one for control and the other for data. Control time slots provide two major functionalities: they provide a random access channel for end users so that users can discover the network and request admission to the network. Control slots also provide a means for access router to exchange control messages among themselves without error for such operations as network discovery, routing table construction and resource negotiation. The network employs the control time slot assignment protocol presented in [6], through which each wireless AR acquires a broadcast time slot that supports a minimum average signal-to-interference-plus-noise ratio (SINR) over the first control subslot (tBUSY in Fig. 2) to all of its neighbors. On the other hand, data time slots are used for transferring user data. The network uses the medium access control protocol [7] combined with an enhanced admission control. The protocol allows ARs to negotiate and allocate resources among themselves in a fully cooperative and distributed manner.

2) Routing and admission control:

The network adopts a proactive routing protocol based on minimum-cost spanning trees, similar to the hybrid wireless mesh protocol (HWMP) of 802.11s with mesh portals [8].
In this paper, the link metric is calculated as the physical-layer (PHY) transmission time (or air-time) per unit data over a link under the saturated interference scenario in which the weakest neighbor of a AR barely supports the minimum PHY data rate, and the routing metric becomes the total air-time along a path under the aforementioned saturated interference. In [7], simulation results indicate that the link metric leads to a higher network throughput under modest to heavy session arrival rates compared to the shortest path (or minimum hop) routing metric.

The network employs an admission control policy which checks resource availability toward the best ingress access gateway for the session before admitting a new session. The policy admits a new session only when existing sessions have been allocated sufficient resources at the admitting AR. A session which is not admitted due to insufficient resources is blocked after a maximum number of unsuccessful tries. It can be shown that this admission control policy in conjunction with the resource allocation strategy in [4] can stabilize the network under high session arrival rates unlike the admission policy used in [7].

3) **High fidelity simulation:**

A large time-driven wireless mesh network simulator has been created that implements realistic physical layer characteristics such as radio propagation and co-channel radio interference, and captures the stochastic network behavior due to random traffic arrivals, admission control, and queuing. The simulator employs a novel parallel processing technique to reduce the long runtimes developed in [9] running over a compact supercomputing platform comprising 32 AMD Opteron 64-bit processors interconnected by multi-gigabit Infiniband interconnect links and having 2 gigabytes of memory associated with each processor.

### B. Hierarchical fiber backbone network

1) **Access gateway design:**

The AG combines the functionality of the wireless mesh gateway (MG) and the optical network terminal (ONT) into a logical interface. Fig. 3 illustrates the interworking between the mesh gateway and the network terminal. The access gateway control is employed to provide the necessary mechanisms for information sharing in order to achieve end-to-end resource allocation. Wireless and optical PHY are managed by the MG and the ONT, respectively. This separation allows future wireless PHY upgrade without requiring modification to the rest of the logical interface.

In GROW-Net, AGs are placed at the intersection between wireless and optical networks to maximize visibility to nearby wireless nodes and enable flexible fiber interconnect. To achieve the latter, the AG employs a 1x2 cross-connect structure. Fig 3 illustrates the node design, in which the key reconfigurable router utilizes Mach-Zhender interferometers (MZI). The reconfigurable router enables both flexible bandwidth and power allocation. This allows the AT to flexibly allocate new resources to secondary loop during cell-splitting without interfering with existing operations. The AG also integrates the reflective semiconductor optical amplifier (RSOA) to remain colorless, i.e. without using active laser, and enables the AT to centralize upstream resources.

2) **Aggregation terminal design:**

The AT integrates the function of the OLT and the metropolitan node into a hybrid interface. Fig. 3 also illustrates the novel AT architecture. In the access segment, the AT allocates both downstream and upstream resources using a centralized tunable transmitter. The AT labels downstream packets with link layer identification (LLID) according to the AG assignment and packets are stripped at the receiving AG.

To aggregate upstream traffic from the AG, the AT sends an aggregation control header (ACH) downstream and follows the ACH with a continuous wavelength burst. The ACH is embedded in the downstream data channel and it contains information about the upstream AG map, allocated wavelength, and length of the sub-burst. The upstream wavelength assignment and traffic grooming technique are described in following subsections.

3) **Hybrid TDM/WDM MAC for local distribution loop**

In GROW-Net, the resources allocated to individual AGs are centralized by the AT. The allocation between upstream and downstream traffic strictly depends on the available metropolitan resource. Upstream traffic slots are allocated to the AG only when the AT determines that a metropolitan resource is available. The wavelength is determined by the metropolitan transport protocol and the duration of the sub-
burst time slot is determined by previously reported upstream traffic request.

During idle slots where metropolitan resource is not available, the AT dequeue local traffic toward the AG using an allocated wavelength channel and proceeds it with the downstream control header (DCH). The AG listens exclusively on the control channel and switches the receiving channel when it receives a DCH or ACH. It strips the packets with its LLID when it receives a DCH. The AG prepares for upstream transmission when it receives an ACH.

In order to collect an upstream request from the AG, one approach is to utilize an array of WDM receivers to directly collect upstream requests using downstream data channels. The AG would dynamically report their queue length following their received data. However, this approach imposes a high hardware cost and is not scalable to the number of data channels in the distribution loop. Thus, GROW-Net’s AT uses a dedicated low speed control channel to receive upstream requests. The AT would periodically pull an AG by sending a REQUEST message embedded in the data channel. The AG would switch to the control channel and respond with a REPORT message to the AT. The control channel wavelength is also allocated from the AT.

4) Metropolitan transport and traffic grooming:

The AT transports local traffic toward the POP using a metropolitan WDM burst transport protocol. The POP utilizes an array of fixed receivers and hierarchically distributes the wavelength resources to groups of aggregation terminals. The hierarchy allows the aggregation terminals to negotiate the metropolitan wavelength resources within a smaller group of terminals. Within each group of terminals, resources are distributedly negotiated using a wavelength token. The token circulates around the terminals and a terminal can transport local traffic using the wavelength labeled by the token. The terminal holds onto the token during transport and releases it when the transport is completed.

The terminal grooms upstream traffic according to the requests it accumulates and aggregates individual traffic using a continuous burst of wavelength. When the aggregated burst returns to the AT, it passes the WDM filter and is directly transported over the metropolitan backbone without optical-electro-optical (OEO) conversion.

IV. JOINT EVOLUTION STRATEGY

The bandwidth required to support "broadband-like" experience, according to the ITU standard, is determined to be above 2Mbps for stationary users and 144kpbs for users in vehicles [10]. In a large scale wireless access network, there are many end users and a significant throughput rate is required at the router to support such requirements. This section examines a feasible upgrade to meet these requirements in a cost-effective and graceful way.

A. Micro-Femtocell cell splitting

GROW-Net enables an innovative micro-femtocell cell splitting method based on a unique structure of the access gateway. The cell splitting method requires a higher density of AG throughout in a fixed region and thus requires more fiber drop points. GROW-Net AG employs the flexible MZI router which allows it to route new and/or existing wavelength to previously idle fiber ports. When comparing GROW-Net distribution loop to a tree-based distribution network such as PON, GROW-Net provides much higher infrastructure sharing and increased protection due to its ring-mesh topology.

B. Graceful optical WDM capacity enhancement

When more AGs are added to the network and more terminals are created to support these AGs, more optical bandwidth is required to support the aggregated wavelengths. Since the AT centrally allocates all wavelength resources to the local distribution network and manages connections to the backbone metropolitan network, the upgrade of wavelengths in the network only requires AT upgrades. AT upgrades can be cost-effectively accomplished by inserting additional tunable lasers in front of the wavelength multiplexer. Corresponding addition of receivers at the POP is also required. The upgrade process is graceful and scalable because it prevents changes at the AG and in existing traffic.

V. THROUGHPUT ANALYSIS AND DISCUSSION

A. Simulation scenario and results

1) Simulation setup:

We simulate urban areas with buildings and streets. Streets are spaced 100 m on a 120 x 120 square grid with access routers located at every street corner. Access gateways are co-located with a subset of AR and the ratio of the number of AGs to the number of AR can vary. Ratios of 1:40, 1:20 and 1:10 are simulated in this paper. We simulate a toroidal universe in which a radio signal propagating out of the universe reappears at the opposite edge and continues to propagate in the same direction. We include interference from all co-channel interferers in the toroidal universe when calculating the average received SINR.

Stationary end users arrive uniformly across the network according to a Poisson process, and each user generates one session. Sessions are best-effort web traffic and each session generates one page. The page size is Pareto distributed with \( \alpha = 1.7584 \) and \( \beta = 30458 \) bytes, resulting in the mean size of 70.6 kilobytes. Each slot comprises one control time slot and one data time slot, each being 1 msec long. There are 70 slots in each frame, and thus, one frame is 140 msec long.

2) Throughput analysis:

Figs. 4 and 5 present two performance metrics for the simulated system: Fig. 4 shows the mean network throughput while Fig. 5 presents the mean session throughput, both for successfully completed sessions. Network throughput is calculated as the aggregate data size of successfully completed sessions throughout the network per unit time, and session throughput is calculated as the session data size divided by the session delay, where session delay is measured from the time a session is admitted to the network to the time the best ingress AG of the session completely
In an overloaded condition, it becomes critical to properly control the admission of new sessions so that the already admitted sessions continue to be serviced with an acceptable quality. If the admission control is too loose, more sessions would enter the network than the network can support. As a result, the network may become unstable and the number of sessions being served in the network may keep increasing with the quality of service continuing to degrade. As Fig. 5 indicates, the admission control policy in this paper in conjunction with the resource allocation strategy in [4] can stabilize the network under high session arrival rates, and thus guarantee a mean session throughput even under heavy traffic loads.

As the network deploys more AGs, the network throughput can significantly improve as shown in Fig. 4. The figure shows the network throughput under different ratios of the number of AGs to the number of ARs. We note that the increase in the network throughput under heavy traffic loads is highly nonlinear as a function of the ratio. The throughput increases about 1.5 times and 2.3 times under the ratios of 1:20 and 1:10, respectively, compared to the case of 1:40. One can consider two factors to explain the network throughput behavior under the different ratios. One is the average number of total transmissions (or number of hops) for each packet to reach its best ingress AG. The number decreases with a larger ratio and thus leads to a lower interference level in the network and a higher network throughput. The other factor is the constraints imposed on the usage of data slots at ARs co-located with AGs. With a higher ratio, fewer constraints are imposed on the usage of data slots at those routers because each AG supports fewer ARs. As a result, fewer data slots are generally required to support a new session. Because each of these two factors varies highly nonlinearly as a function of the ratio, it appears not straightforward to model the network throughput as a function of the ratio.

VI. ENABLING TECHNOLOGIES FOR THE RECONFIGURABLE OPTICAL TESTBED

In this section, we first present the enabling technologies for the devices we have designed, fabricated and used in the GROW-Net’s reconfigurable optical testbed. The optical backbone relies on a versatile MZI to construct the wavelength and power distribution device. We exploit the fact that a single MZI stage can be operated in a power splitting mode or a wavelength de-interleaving mode.

A. Enabling reconfigurable technology

MZI is the enabling technology to the reconfigurable device employed in the access gateway. The operation of MZI relies on refractive index change can be controlled by either thermo-optic or electro-optic means. For a single wavelength, the power splitting ratio can be varied between 0 and 100%, as shown in Fig. 6(b), by applying a voltage between 0 and \(V_r\) on one arm of the MZI. By positioning the voltage at the point circled in the figure we could achieve a 50/50 splitting ratio for all wavelengths entering the stage – as shown in Fig. 6(a). Alternatively, the MZI can

![Figure 4](image-url)  
**Figure 4.** Mean network throughput vs. session arrival rate under different ratios of the number of access gateways to the number of access routers.

![Figure 5](image-url)  
**Figure 5.** Mean session throughput vs. session arrival rate under different ratios of the number of access gateways to the number of access routers.

releases resources allocated to the session. Each data point is obtained from one long simulation run which takes several days up to a week using 16 processors simultaneously.

At a very light traffic load, e.g., \(\lambda = 0.05\) (sessions/sec/access router) for the ratio of 1:40, the network throughput increases almost linearly as a function of the session arrival rate, implying that most of the sessions arriving to the network are successfully transferred to the AGs. As the session arrival rate increases, the interference level across the network increases and PHY data rates supportable on data slots decrease. Consequently, more data slots are required to support the increasing traffic loads. If the session arrival rate keeps increasing, at some point, all the data slots available to the network are exhausted and the network becomes overloaded. For example, the network starts to saturate at around \(\lambda = 0.1\) and becomes heavily overloaded at about \(\lambda = 0.20\) for the ratio of 1:40.

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the set \( \lambda_2, \ldots \), will be routed to output port 1, and any wavelength in the set \( \lambda_1 \) also be used as a wavelength switch/interleaver. For a single MZI, any wavelength in the set \( \lambda_o+2\Delta\lambda L/k \), where \( k = 0, 1, 2, \ldots \), will be routed to output port 1, and any wavelength in the set \( \lambda_4+2\Delta\lambda L/k \), will be routed to output port 2 at a specific voltage \( V \). Fig. 7(b) shows the transmittance spectra for the two output ports of a MZI.

### B. Experimental Results

We have fabricated a 1:16 reconfigurable power splitter and wavelength router with the former option using 2 double-stage MZI’s. The stages are designed to be de-interleaving stages with successive ratios of 50:100 GHz, 100:200 GHz, 200:400GHz, and finally 400:800GHz. Thermo-optic heaters were added to the arms of each stage for fine-tuning the phase difference between the arms for optimal operation as a de-interleaver as well as coarse-tuning for variable power splitter operation. Fig. 8 shows the measurement results of the fabricated two-stage cascaded MZI based reconfigurable device. The plots show the output optical power level at each one of the four output ports of the cascaded MZI when only one wavelength is provided. The results show more than 16dB of suppression and power selection ability for the proof-of-concept device.

### VII. Conclusion

This paper presents a novel hierarchical and large scale hybrid access network architecture called grid reconfigurable optical-wireless network (GROW-Net). The architecture enables scalable and flexible integration of fiber and wireless mesh in a large scale municipal access network. First, the throughput analysis of the large scale wireless mesh network is presented using a high fidelity simulator. Moreover, the degree of throughput enhancement in municipal environment is presented jointly with a scalable and reconfigurable backbone that supports flexible femtocell splitting. A MZI based architecture for the reconfigurable device is fabricated and its performance is presented.

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