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A Review of Integrated Optical and Wireless Broadband Acess Networks

S. H Mohammad[a*], N. Zulkifli[a], S. M. Idrus [a]

[a]*Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru*

*Corresponding author: hasunah@fkegraduate.utm.my

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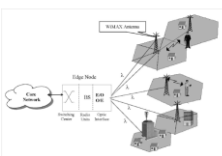
Graphical abstract



Abstract

Broadband access network nowadays has obtained increasing attention among internet users. High bandwidth demands and the need on mobility of the network cause the network design and architectures to be part of the hot topics in the research area. Wireline optical and wireless networks are two different architectures of broadband access network which offer advantages over each other. High capacity optical network integrated with tetherless wireless network enables high-speed communications to mobile users at anytime and anywhere. This paper defines integrated optical wireless broadband access network, outlines the architectures of different network models, the features and key issues of the network.

Keywords: Optical access network; wireless access network; integrated optical wireless network; passive optical network; wireless mesh network

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■1.0 INTRODUCTION

The increasing demands for bandwidth services are rapidly rising up the need to design an economically "last-mile" access network. Existing optical access network and wireless access network have their limitations in providing the users with multimedia services. Optical access network such as Passive Optical Network (PON) which is used in Fiber-to-the-Home (FTTH) technology provides high bandwidth and proven reliability and have a rich history of supporting data and video applications [1], but optical network alone has its limit in coverage as it is a fixed wireline network. On the other hand, wireless access network has the benefits of mobility and flexibility, removing the constraints of time and place but it provides less bandwidth than optical fiber access network.

Recently, Wireless Mesh Network (WMN) has come out as a promising technology for the next generation wireless networks. Two types of nodes of a WMN are known as Mesh Clients (MCs) and Mesh Routers (MRs). The MRs are used to form an infrastructure to forward the traffic between MCs and the Internet, but MRs are limited in mobility and they operate just like a network of fixed routers. The difference is they are connected by wireless links through wireless technologies. Only a few of MRs are needed in connections with wired network, thus a WMN can reduce the installation cost of the broadband access network [2]. Since it is a multi-hop network, it provides longer distance of coverage, so the large-scale deployment through intermediate nodes can be built. The new competitive wireless mesh type of network with high bit rates, such as Worldwide Interoperability for Microwave Access (WiMAX) [3] can be utilized to improve the performance of the network. As illustrated in Figure 1, optical fibers are used to connect an edge node in a central office, to WiMAX base station antennas which may each certainly serve large number of subscribers in a relatively large cell.

Obviously, optical network and wireless network are two diverse technologies, but these two networks complement each other if they are designed jointly to build a single network infrastructure. With optical network at the back end and wireless network at the front end of the infrastructure, the high capacity and flexible broadband access network can be deployed exploiting the extended coverage and high bit rates of existing WMN. The integrated optical wireless architecture also can link the service between rural and urban areas in economic way, exploiting the benefits from the converged network. Many works have been done to explore this type of network, noting the high-capacity and cost effective integrated optical wireless broadband access network. Lately, its deployment has been applied in the field of access network in many cities around the world.

This paper reviews the integrated optical wireless broadband access network. Some advantages and features of the converged network are highlighted in Section 1.2, with a few integrated models of optical wireless broadband access network are investigated in Section 1.3. Then, the research issues in this area are outlined in Section 1.4. Conclusions are drawn in Section 1.5.

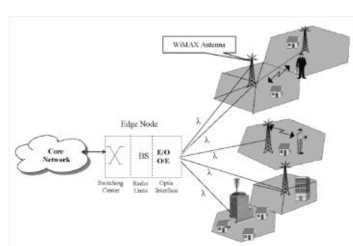

Figure 1 Optical fiber and WiMAX integration [3]

2.0 ADVANTAGES AND FEATURES OF THE CONVERGED NETWORK

Integrated optical and wireless broadband access network offers benefits which attracted the researchers to involve in this area. The advantages of this converged network are:

2.1 Cost-effectiveness

Fiber optic cable surely has many advantages if it is used in broadband access network. Due to it high rates of data transmission and low attenuation, it has been selected as data transfer medium even for longer distance with little data loss. In contrast, fiber optic alone as broadband access network can cost more than double what a typical broadband connection costs because in all-optical network, installing and maintaining the fiber all the way from the central office (CO) to each user could be quite expensive. It has been studied that according to the 2001 U.S. census figures, there are 135 million houses in the U.S., and in evaluation, to wire 80% of the U.S. households with broadband access network would cost in the range of $60-120 billion, while wireless connections would cost only $2 billion [4].

With improvement in converged optical-wireless network, there is no need for expensive FTTH connectivity as each user will connect to its neighborhood Optical Network Unit (ONU) in a wireless manner. Wireless routers are used to connect each user to the Internet via multiple hops. Optical fiber infrastructure is used to send the user's processed data from the ONU to the Optical Line Terminal (OLT). Thus, the deployment cost of fiber to user's premise can be reduced. Some researchers also have done a work to make this converged network more affordable such as in [5]. They optimized the BSs and ONUs placement by using a model named Mixed Integer Programming Model (MIP).

2.2 Flexibility

With no wires or cables to route, a wireless network is essentially more flexible than other network. Users are not locked into a fixed network topology or system setup, leaving open the possibility for additions, upgrades, extensions, and so on. Exploiting this ability into integrated optical wireless network gives users the freedom to move while using the multimedia services. The wireless part at the front end of this architecture allows the users in the service area to connect to each other easily compared to optical access network alone which provides services in a fixed wireline. As long as the users are within the wireless network area, they are able to use the multimedia services.

Recently, Wireless Fidelity (WiFi) and WiMAX have been the common wireless network favored by the large-area users. WiFi, which is one of the most popular wireless technologies with standard of IEEE 802.11a/b/g is mainly used for wireless local-area network. It can utilize the flexibility of multihopping, but the bit rates offered are lower than that of WiMAX. With standard of IEEE 802.16, WiMAX can be used for single-hop communication providing high bandwidth and high bit rates. Thus, WiFi and WiMAX are suitable technologies for the front end of this converged network due to their mobility features.

2.3 Robustness

In a traditional PON, fiber cut will fail the ONU connected to the splitter. Even bad, if a trunk from OLT to the splitter breaks, the entire ONUs will fail, affecting all the users served by the ONUs. In July 2010, there was a case in Pittsburgh where Verizon Communications Inc. business customers in three states, including Pennsylvania, experienced service disruptions after a fiber optic line was cut in Hagerstown, Md. [6]. The 1,000-foot cable was damaged by a tree falling on an aerial fiber line near railroad tracks. The cable was snagged and damaged when a train passed through the railroad. The damage caused the users to take some times to reset and restore their system.

Compared with the converged network, in case of an ONU failure, affected users may be able to find a neighboring live ONU through the wireless mesh to redirect their traffic to the CO. This is due to the ability of the users to form a multihop mesh topology which then helps the system to adapt itself. The ability to reroute the traffic through the adaptive multi-hop mesh topology makes the converged optical wireless network more robust than traditional wireline in case of failures.

2.4 Transport Capacity

Optical fiber link is known as the data transfer medium which provides very large bandwidth that is far in excess of the wireless and any other known transmission medium [7]. Earlier in the beginning of optical fiber systems, a high-capacity network was capable of operating at several million bits per second (Mbit/s) over some form of metallic medium such as copper wire or coaxial cable, or over wireless systems such as microwave. On the contrary, optical fiber systems transmit light signals through a glass or plastic medium. These systems are many orders of magnitude "faster" than their predecessors, with the capability of operating in the terabits-per-second (Tbit/s) range.

Optical signals used in optical networks operate in a very high position and range of the frequency spectrum, many orders of magnitude higher than electromagnetic signals [8]. Thus, many more user payloads can be sent onto the fiber medium because of the use of the higher frequencies. As a result of the convergence of optical and wireless network, the network would have high capacity than the traditional wireless network because it owns high-capacity optical trunk at the back end.

2.5 Reliability

Over several decades, the manufacturers have been improving the Ethernet technology and produced extremely reliable Ethernet cables, hubs and switches. Loose cables likely remain the single most common and annoying source of failure in a wired network. When installing a wired Local Area Network (LAN) or moving any of the components later, the cable connections must be carefully checked.

Broadband routers have also suffered from some reliability problems in the past. Information lost due to interference in traditional wireless network causes the network to have poor throughput. Broadband routers have matured over the past several years and their reliability has improved greatly. On the other hand, the integrated network is more reliable as problem of congestion and information lost is not as much of the current wireless network. In addition, better load-balancing capability is provided as user is able to communicate with any other ONU in its region if its primary ONU fails.

2.6 Self Organization

Its fault-tolerant capability and its robustness due to adaptive wireless mesh and load-balancing features make integrated optical wireless network a "self-organizing" network. The converged network has the ability to "heal" itself if there is any failure in the system and the infrastructure. For example, the design of integrated failure recovery techniques allow the traffic to be rerouted via wireless networks in the event of fiber cuts in the optical access network.

In “self-healing” mechanism, a router does not always need to recompute a new set of paths even if a failure occurs. In [9], router will recompute paths only if all its previously computed paths fall under Primary Gateway Group (PGG) and the ONUs/OLT fail, or all paths fall under PGG and Secondary Gateway Group (SGG) and the corresponding OLT fails. After path-recomputation, packets will be admitted in the network with degraded service because of increased delay.

2.7 Incentives

The cost to provide wireline broadband connectivity is extremely expensive as the contractors have to maintain the fiber link all the way to customer’s home. In many developing regions of the world such as in Japan, Korea, and Europe, fiber is deeply deployed (within 20 km) even in the countryside. In France, FTTH connection costs are estimated to be around 2000€ in most densely populated areas (i.e. Paris) and rising to 5000€ for average density areas [10].

The governments have decided to provide incentives to the operators and contractors to deploy the infrastructure which alike integrated optical wireless broadband access network so that the challenges in wireline development (i.e. expensive cost, time consuming, and difficult maintenance) can be avoided [11].

3.0 INTEGRATED MODELS OF OPTICAL WIRELESS BROADBAND ACCESS NETWORK

Integrating two diverse technologies is more challenging than only an optical or a wireless access network deployment. Some works have been done to deploy this type of network to replace the existing broadband access network.

3.1 Wireless Optical Broadband Access Network (WOBAN)

Sarkar *et al*. in 2007 has proposed a multi-domain hybrid network [4]. Figure 2 shows the architecture of a WOBAN. A WOBAN consists of a wireless network at the front end which could be either a WiFi or WiMAX, while at the back end; it is supported by an optical network. In this model, OLT which is placed in a telecom central office plays its role to feed several ONUs. From ONU to the CO, WOBAN is connected by fiber links, then the ONUs are connected to the users wirelessly in single-hop or multi-hop fashion.

The optical part of WOBAN is assumed as a tree, while a mesh is visualized in its wireless front end, which is formed together by the wireless gateways and routers. In this multi-domain architecture, multiple wireless routers can be associated with a single gateway. The gateways are primary aggregation points. The OLT in the back end acts as the parent of the tree with wireless gateways as leaves and ONUs as children in between. Since multiple gateways can connect to one ONU, the ONUs are higher aggregation points. Thus, the highest aggregation point for the WOBAN is the OLT before the traditional metro/core aggregation occurs for the rest of the network.

3.2 Grid Reconfiguration Optical and Wireless Network (GROW-Net)

Shaw *et al.* in [12] has proposed another WOBAN-like architecture which is called GROW-Net. This architecture consists of a WMN in the front end and a reconfigurable optical network as the backhaul. The WMN is used to provide low-cost service to the user everywhere. It deploys multiple wireless mesh routers to exchange traffic via gateways which are connected to the Internet through the PON. The optical backhaul of GROW-Net is driven by a high capacity, point-to-multipoint PON which consists of a ring and multiple tree networks. The OLTs also belong to the ring while the ONUs are connected to the gateways of WMN in GROW-Net. The architecture of GROW-Net is shown in Figure 3.

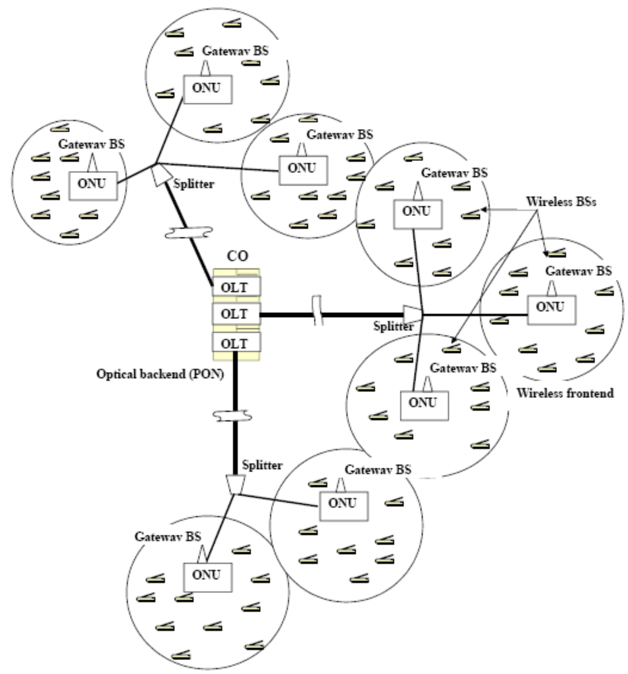

Figure 2 WOBAN architecture [4]

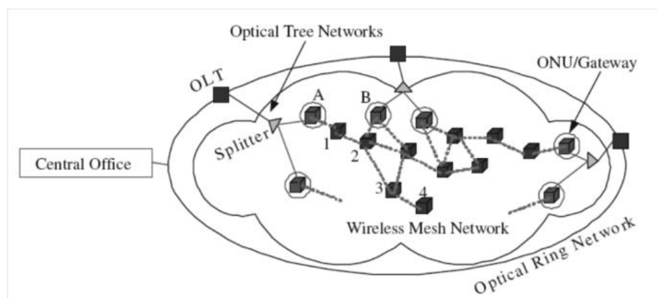

Figure 3 GROW-Net architecture [11

Due to its limited or no mobility, less power constraints, and enhanced computational capabilities, the WMN of GROW-Net is “infrastructure” based. The reliability and load balancing in the WMN of GROW-Net is improved by exploiting the traffic operation in the mesh network. The authors in [12] also suggested that further study on the practicability of wireless technologies is needed to improve the capacity, reliability, maintenance, and mobility of WMN in GROW-Net.

3.3 Optical Wireless Integration (OWI)

In 2010, the authors of [1] has projected Optical Wireless Integration (OWI) architecture, which is a natural step from Fixed Mobile Convergence (FMC). In this architecture, WiMAX technology is proposed to be the wireless front end of the OWI architecture to provide the last-mile broadband while PON is applied as the optical backhaul. OWI architecture consists of point-to-multipoint WiMAX combined with Multiple Input

Multiple Output (MIMO) technology (see Figure 4) to improve the capacity of wireless front end.

Multiple element arrays which are spatially distributed are used to exploit the space range of wireless channels in MIMO. It also exploits multipath propagation with no extra spectrum while its links are used to synchronize antenna resource allocation among WiMAX base stations. In case of base station failures, a centralized antenna assignment algorithm at the OLT will exploit MIMO diversity to achieve better throughput and flexibility.

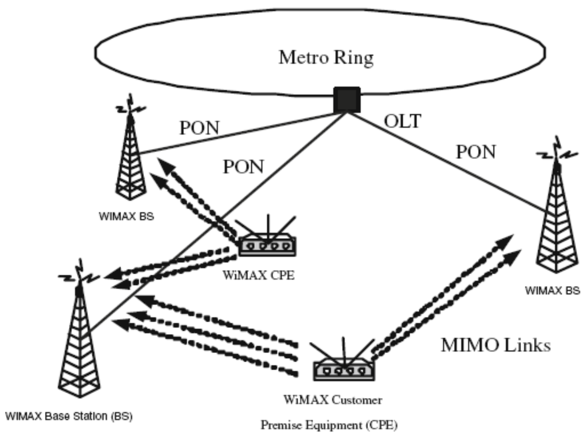

Figure 4 OWI architecture [1]

4.0 KEY ISSUES OF THE CONVERGED NETWORK

In deploying the integrated optical wireless broadband access network, there are some issues that motivated the researchers to keep on improving the technology. Mukherjee in [13] has stated some of the issues and a few of them are as follows:

4.1 Node/Router Placement

In order to save the deployment cost, the placement of ONUs or gateways should be made properly because the optical and wireless parts are met there and the network performance is largely depends on them. As example, for WOBAN, a few schemes on ONUs placement have been proposed such as deterministic, greedy, simulated annealing, and mixed integer programming [11]. These algorithms focus on finding a strategic placement of multiple ONUs/BSs in economical way considering the location of the users. The pros and cons of each of the schemes are shown in Table 1.

Table 1 Pros and cons of various placement approaches in WOBAN

Placement Scheme	Solution Quality	Processing Time
Deterministic [4]	Better	Constant
Greedy Algorithm [14]	Good	Linear (in practical cases)
Simulated Annealing [15]	Improved over Greedy	Depends on convergence criteria
MIP [5]	Optimal	Very high

Deterministic scheme is proposed to arrange the placements of ONUs in WOBAN. Deterministic works well for symmetric topology and no prior optimization is needed in this approach. Greedy is the lowest complex among the four schemes. Manipulating divide-and-conquer heuristic, it is a good solution for uniform distribution of users. Greedy is improved by Simulated Annealing (SA), a combinatorial optimizer scheme which may not converge for discontinuous cost model. The most complex analytical solution is MIP because several constraints must be considered. This model predicts setup costs in dollars. More details on these schemes can be referred in [4, 5, 14, 15].

4.2 Routing

Information (data packets) routing through the converged network is a main challenge and very important problem because it involves two diverse technologies combined together, not optical network or wireless network alone. Some of the routing algorithms have been proposed for the integrated optical wireless broadband access network as stated below:

4.2.1 Delay Aware Routing Algorithm (DARA)

Sarkar *et al*. has proposed DARA [17] in 2007 to focus on the packet delay in the wireless mesh of the converged network (i.e WOBAN). Routing in DARA is based on two decisions, which are: the associativity of a user to a nearby wireless router in its region and the path from this route to a suitable gateway through the wireless mesh. It is based on the following principles: wireless-link-state updates, link-state prediction, link-weight assignment, path computation/selection in wireless mesh, traffic aggregation in upstream gateways, and admission control. The center of attention in DARA is to find a path that minimizes the front-end WMN delay along with better load balancing and less congestion.

4.2.2 Capacity and Delay Aware Routing (CaDAR)

CaDAR is a follow-up work of DARA [18] as it improves the throughput and average packet delay of the integrated network by performing capacity awareness on top of DARA’s delay-aware routing. Using CaDAR, the wireless capacity is distributed optimally only among active links based on the flows of the links. This ensures the links with higher flow to have higher capacity, thus the limited capacity of the wireless nodes can be utilized efficiently. In order to provide best services, CaDAR gathers information of the wireless links, estimates the delay on the links, and performs delay-aware routing by selecting the shortest-delay path in the wireless part of the converged network.

4.2.3 GROW-Net Integrated Routing (GIR)

An integrated routing algorithm is used in GROW-Net to route packets through various routes from central hub to each end user. The integrated routing algorithm, GIR, selects the optimal ONU/gateway for each wireless mesh router at any given network condition depends on the wireless link states and average traffic rates. GIR also performs load balancing. As shown in Figure 5, the following are steps in integrated routing of GROW-Net with details in [11]:

1. Wireless-link-state update
2. Local-WMN route calculation
3. Route-cost report
4. Gateway association
5. Congestion monitoring
6. Congestion report to the route-assignment model
7. Alternative gateway lookups
8. Gateway reassociation
9. Flow control

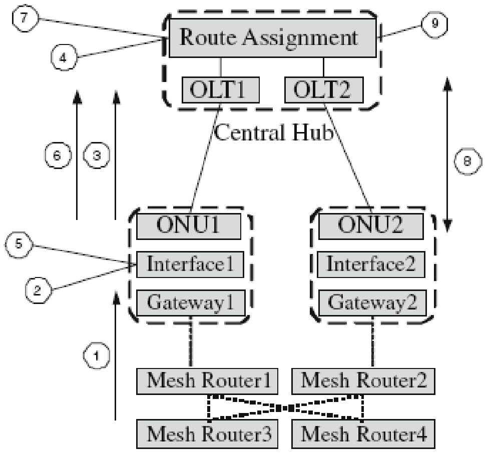

Figure 5 Integrated routing in GROW-Net [11]

4.3 Fault Tolerance

Self-healing and self organization properties are important in future access network in case of failures such as fiber cut, gateway or router failure, and OLT or ONU failure in order to provide the best network performance. Sarkar *et al*. in March 2007 has proposed an algorithm named Risk-and-Delay Aware Routing Algorithm (RADAR) which can handle multiple failure scenarios [9].

In RADAR, the researchers focus on risk awareness, self-healing, and delay-awareness of the network. They modeled each router inside the mesh as an M/M/1 queue. Link-state-advertisement (LSA) will be done by each router periodically. Link weights are assigned to the wireless links based on the LSA information. Links with higher delay are assigned higher weights. The path is computed with the minimum average transfer delay from a router to any gateway. It is important to maintain the Risk List (RL) table in each router because this RL will be updated accordingly in a case of failure. Then, the subsequent packets will be rerouted. Besides, researchers also proposed GROW-Net's Reconfigurable Backhaul [12], the reconfiguration which helps in minimizing the performance degradation.

4.4 Topology Formation

Although the topology of the access network is reasonably simple, the planning of customer connections, in terms of traffic rates and accounting, Quality of Services (QoS), and routing policy, occurs here. The configuration and maintenance must be executed carefully because the consequences of a router misconfiguration can be severe. To ensure this, the wireless mesh front end should be adaptive and self organizing to create a mesh topology after initial deployment or after failure. The researchers are encouraged to design the effective recovery techniques in case of failures which can reduce the maintenance cost of the network.

Lu *et al.* in [18] proposed a topology control scheme taking into account the transmission range, the type of antenna, the traffic pattern and QoS to maximize the overall throughput capacity. Near optimal throughput capacity can be obtained by setting up multiple wireless highways on both the horizontal direction and the vertical direction. Based on the topology, they built efficient scheduling schemes that utilize advanced technologies, including network coding and physical-layer network coding (PLNC). Besides, the authors in [19] have proposed a topology control framework for service-oriented WMNs highlighting that there is a need to address the demands from the upper layer applications. Chen *et al.* have proposed a greedy selection rounding (GSR); an efficient and near-optimal algorithm to design a wireless mesh network topology that maximizes the coverage of the users while ensuring that the network is resilient to node failures and the deployment cost is under a given budget [20].

4.5 Channel Assignment

It is important to investigate the orthogonal channel assignment techniques taking into account of connectivity, demands and interference in the WMN to reduce the signal interference. Efficient channel assignment schemes can greatly reduce the interference effect of close-by transmissions while effective routing schemes can alleviate potential congestion on any gateways to the Internet. Combining these two approaches possibly can help in improving per-client throughput [21].

In [22], the authors described different schemes which are classified as Static, Dynamic and Hybrid Channel Assignment that can be used to assign channels in a WMN to achieve efficient channel utilization and minimize interference. Researchers in [21] have mathematically formulated the joint channel assignment and routing problem, considering the interference constraints, the number of channels in the network, and the number of radios available at each mesh router in WMN. They have proven that their proposed algorithm can successfully exploit the increased number of channels and radios, and it performs much better than the theoretical worst case bounds. Further research on this topic is needed to realize the full potential of converged network architecture.

4.6 Joint Design

Optical network and wireless network are very different in their architecture and infrastructure. The procedures and components needed in deploying these two networks even before convergence are also widely varied. In order to integrate these two networks, both optical and wireless parts must be designed jointly to complete each other. The optical part has to be designed to help the wireless part to overcome its capacity limitation, whereas the wireless part has to be designed effectively to broaden the coverage of optical network. Fail to properly integrate both networks will cause complex computational configuration later.

5.0 CONCLUSION

It is clear that the main issue in the optical wireless broadband access network is how to integrate the optical and wireless technologies in order to provide the efficient access network for Internet users. Many points such as routing algorithm and router placement are very important to reduce the deployment cost of the technology. Research in this area is still on-going. In the future, there will be indistinct boundary between these two technologies and the cost of components will be reasonably priced as the commercial volume increases. Thus, it would be practical and affordable to set up and manage the future integrated optical wireless broadband access network.

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