

Usage Scenarios and Application Requirements for Wireless Mesh Networks^{*}

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Abstract

Reduction of network deployment and operation costs and integration of wireless access networks with fixed broadband access technologies is a key enabler for small and medium scale enterprises to enter the rapidly growing mobile broadband access market, and introduce innovative services that require pervasive broadband access. Mesh Networks represent an emerging wireless networking technology that promises wider coverage than traditional wireless LANs and higher data rates combined with lower deployment costs than 3G mobile networks. In order to turn the outstanding business potential represented by mesh networking into real profit, one needs to solve a number of technical problems related to the design and operation of mesh networks. Starting point to this direction is to define the system requirements both in terms of available services and applications, and in terms of their usage by end users.

1. Introduction

Mesh networks [1, 2] represent an emerging wireless networking technology that promises wider coverage than traditional wireless LANs and lower deployment and operation costs than 3G cellular networks. For these reasons, network operators and service providers consider mesh networking to be a serious candidate to solve the so called *last mile problem*. Some network operators have already started

to deploy mesh based access networks offering nearly ubiquitous and inexpensive wireless Internet connections to their customers. Examples of this development include *Ozone's* mesh network in Paris (www.ozone.net/en/) and *The Cloud* in the City of London (www.thecloud.net). If these pilot projects turn out to be as successful as expected, then mesh networks will become extremely popular and widespread.

Although existing community based mesh networks are operated by individuals, the real business potential lies in operator based mesh networks. By their systematic design, deployment, and maintenance, operator based mesh networks provide higher levels of Quality-of-Service (QoS), meaning larger coverage, higher speed, and more reliable operation. In addition, it can be argued that mesh network operators in a given geographical area will cooperate in order to further optimize their costs and increase the QoS provided by their networks. The form of the cooperation can range from traditional roaming agreements to joint provision of specific services. Hence, in this paper, we focus our attention on QoS-aware mesh networks operated by multiple operators.

Starting point to this direction is to identify the usage scenarios for wireless broadband services that will be offered over wireless mesh networks, and the corresponding service and application requirements and functionalities that a multi-operator based QoS aware mesh networking system should support. The paper focuses on the following two directions:

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identification of the community of users that could derive social and economical benefits from such a mesh network, and

definition of the technical requirements and functionalities that the system should provide in order to support services and applications.

The rest of the paper is organized as follows: We start by discussing the radio access network and describing the multi-hop mesh topology employed. Next we identify the services and applications that will be supported, and the classes of users that will use them and can obtain benefits from the proposed system architecture. Based on the services/applications and user classes, we next identify representative usage scenarios, and from these the corresponding high level user and applications requirements. Additionally, we identify the requirements from the network and service provider's side. Finally we describe the technical requirements related to mobility, security, resource management, and cross-layer monitoring and emphasize on the QoS requirements.

2. RAN & multi-hop mesh topology

When user devices connect to the access network through an air interface, as in the case of mobile networks, the access network is referred to as radio access network (RAN). RANs represent a significant percentage of the overall network costs, which is typically in the range of 25-50%, hence their efficient operation is important [3]. Moreover, the importance of the access networks is justified by the fact that there is not much opportunity for significant improvements at the link layer. The above, in addition to the need for supporting increasingly high bandwidth creates the following requirements for future access networks [4]:

High data rates and capacity, High reliability and QoS support, Lower cost, Flexibility and reconfigurability to adapt to increasing demand, Incremental deployment and scalability, Spectrum efficiency and efficient usage of backhaul capacity, Seamless inter-working with multiple (heterogeneous) radio technologies.

The above requirements translate to the following trends for future radio access networks [5, 6]:

High density deployment of base stations (microcells). This reduces the distance between end-user devices and base stations, hence reduces the corresponding path loss. On the other hand, higher densities mean higher costs, thus increasing the importance of cost-effective operation of radio access networks.

Evolution towards packet switched IP-based nodes. This allows utilization of open interfaces, which eventually leads to reduced cost for the radio access network.

Shifting all or most radio functions to base stations, i.e. the devices to which the end user devices directly connect to.

Sharing of the radio access network between multiple providers.

Flat/distributed architecture, with peer-to-peer (or many-to-many) connections between nodes. This reduces the cost for each node, enables higher flexibility, scalability, redundancy, and reliability.

Distributed control. This avoids single points of failure, hence increases the access network's reliability.

The topology considered for multi-operator based QoS aware mesh networks is the multi-hop mesh topology as shown in figure 1. With this topology the end-user access nodes connect to core network nodes through one or more nodes in the radio access network through multi-hop wireless links. Wireless links between access network nodes can be optical links (free space optical technology at 785 or 850 nm – infrared, or 1550 nm near-infrared), microwave (30-40 GHz), millimeter wave (60 GHz), Wimax and links in unlicensed bands (802.11b/g, 802.11a, etc).

A multi-hop mesh topology further enhances the reliability, since an end-user access node is not only connected to multiple core network nodes, but additionally there are multiple paths between an end-user access node and a core network node. The advantages for such a topology have been identified in [3, 7].

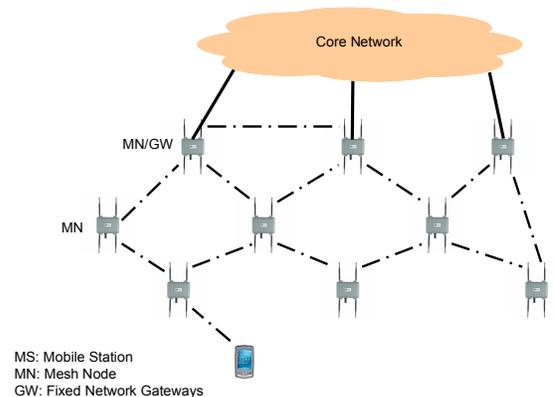


Figure 1. Multi-hop mesh topology

Mesh topology is also used in community, municipal, and commercial city-wide deployments that utilize commodity 802.11 hardware. A mesh topology

is also considered in WiMAX's 802.16a mesh mode, which allows the connection between a mobile station and a base station through other mobile stations. Related protocols for supporting mesh connectivity with 802.11 wireless links is being defined in the 802.11s task group. Indeed, the trend towards mesh and multi-hop connectivity within the radio access network has been identified in a number of papers, e.g. [7, 8, 9].

3. Services and applications

The categorization of services and applications is a superset of the user-perspective QoS classes identified in [10, 11], which differentiates classes based on how delay sensitive the corresponding applications are. The QoS classes of service are the following:

Conversational class: This involves real-time communication between peers (or groups) of live (human) end-users. The communication can involve audio, video, or text. This class has the most stringent requirements in terms of end-to-end delay.

Interactive class: This involves the online requesting of data from an end-user (human or machine) to a remote server. The primary performance metric for this class is the response time.

Streaming class: This involves real-time transmission audio or video streams to end-users, which are assumed to be human. The main performance metric for this class is the delay variation of the transmitted traffic.

Background class: This involves the transmission of data in the background. This class does not impose any requirements in terms of delay.

The categorization presented below, firstly differentiates basic Internet services, and includes new services/application categories, which are expected to play a significant role in emerging ubiquitous broadband access networks.

Basic Internet services (Web browsing, Email, multimedia messaging, etc).

Conversational services (VoIP, video-telephony, Tele/video-conferencing, Instant Messaging, Online chatting etc).

Streaming services (like IPTV: Transmission of digital television over an IP network infrastructure).

Interactive services (like Interactive gaming and E-commerce applications).

Multimedia sharing (like Peer-to-peer file sharing)

Context-based information services (context can be the location, presence, profile, behavior, etc).

Services can also be categorized in terms of other features, such as real-time/non-real-time, user-generated/server-generated content and

symmetric/asymmetric requirements for downlink and uplink.

4. User classes

User requirements do not depend solely on the service/application performance requirements, but also on the specific characteristics of user classes as well as the usage of the particular service/application. Depending on user classes and usage scenarios, there could be a different tradeoff between cost, security, mobility, and performance requirements.

Table 1. User types

Users Grouped By	Groups Identified
Type of Customer	Home/residential Business users (individual) Private organizations: Public organizations Value added service providers
Usage Type	Fixed: single location. Connection through an outdoor or indoor CPE Mobile: vehicular speeds. Connection through a wireless interface located on the end-user device Nomadic (also referred to as "portable" mode): stationary or moving at pedestrian speeds. Connection through a wireless interface on the end-user device
Type of Device	Laptop PDA Smartphone Set-top-Box Personal Computer Smart Objects (<i>like SPYKE Robot from Meccano with M2M</i>) Standard Phones with WiFi/WiMAX/3G functionality
Purpose of Usage	Business Critical – business, telephone calls, monitoring, security sensitive Entertainment – IPTV, VoD Leisure – Web surfing, tourism guidance Learning – mobile learning Medical – telemedicine application Social Communication – audio/video calls, multimedia sharing

The boundary between user classes is not strict, and is becoming increasingly blurred as the need for mobility increases, and as technology convergence enables new markets and new habits. Table 1 illustrates various groups of users, according to different categorization criteria.

User classification is mainly necessary in order to identify user needs in various contexts and to identify difficulties in broadband adoption. For instance, the needs of a user on the move are very different from that of a stationary/indoor user. Depending on usage type, a user can select a different tradeoff between cost, security, mobility, and performance. This leads to the requirement for personalization of services.

5. Usage scenarios

We consider the following usage scenarios for multi-operator based QoS aware mesh networks:

5.1. Mobile business usage scenario

This scenario involves access to services and applications by business users that are on the move. User mobility refers to the ability of a user to move across the network, using a variety of terminals and points of attachment, while maintaining the same user identity. The key characteristic from the user point of view is seamless mobility.

The network requirements for such a scenario include efficient and scalable QoS support with prioritization, controlled jitter, reduced latency and minimization of packet losses for voice and multimedia traffic, network traffic monitoring and tuning to provide the requested QoS by an assessment of the network's load, existence of mechanisms for secure and fast handoffs between heterogeneous networks and different operators and presence of mechanisms for (automatic) re-authentication during handover. Additionally such a network should be able to adapt to varying network conditions and should provide security mechanisms to ensure high reliability and availability.

The advantages for a multi-operator based QoS aware mesh network include the provision of enough bandwidth to allow smooth service delivery, with strong delay and jitter constraints (especially for VoIP), cost effectiveness and fast and effective handover either within the same access technology or within a network using different kinds of access technologies (like 3GPP / Wifi roaming).

5.2. Nomadic business usage scenario

Nomadic business users are people moving from place to place, that require information exchange and communication services available for business purposes when they stop moving. In this case, they have to suspend an application or a session and resume it when they connect at a new access point.

The network requirements for such a scenario are efficient and scalable QoS support including prioritization, controlled jitter and latency and minimization of packet losses for voice and multimedia traffic, network traffic monitoring and tuning to provide the requested Quality of Service by an assessment of the network's load and mechanisms for fast (automatic) re-authentication between different operators.

Among the advantages for a multi-operator based QoS aware mesh network is that such a network provides enough bandwidth to allow smooth service delivery, with strong delay and jitter constraints (especially for VoIP), it is cost effective and the

provision of network services is equivalent to a fixed business user.

5.3. Gamers usage scenario

Online games are played over some form of a computer network, typically on the Internet. Online gaming offers the ability to play against human opponents (multiplayer games), although single-player online games are quite common as well. Different genres of online games exist, while cross platform online games are possible, allowing users of different kinds of platforms to connect to the game.

The network requirements include low delay and low jitter, higher uplink rates and predictable QoS.

The advantages for a multi-operator based QoS aware mesh network is the ability to play efficiently due to adequate throughput and low delays, the provision of high uplink rates and network service delivery equivalent to a home gamer.

5.4. Home usage scenario

Broadband access in fixed environments, is increasingly utilized for activities related to entertainment, mainly music, television over IP (IPTV) and video (streaming or on demand). Both the technological and the market trends point the way towards increased penetration of triple-play services, which can also be envisaged within the cases of multi-operator based QoS aware mesh network. A usage scenario for such a network can include the case of the fixed home user that i) has the necessary IP-enabled multimedia equipment (STB, Set-Top-Box) at his home to view videos, TV programs and listen to music, ii) has on-demand access to multimedia (movies, music etc) content through content providers, and iii) has access to streaming content and time-shifting viewing capabilities.

The network requirements derived from this scenario are high downlink speeds, with prioritization and controlled jitter, efficient and scalable QoS support, availability, scalability and cost-effectiveness.

5.5. Tourist / attraction visitor usage scenario

This scenario delivers services and free (or for a flat low cost) public access based on the location information and the user personal profile. It also allows people to share their multimedia files (photographs, video, textual notes, etc) with locations on electronic maps with other users.

From the user perspective, the requirements derived from this scenario are ubiquitous access and user

mobility. From the network perspective the system should autonomously detect the user position, it should provide high uplink speed, and it should be resilient to operational anomalies and security attacks, as it should work in a multi-operator environment.

5.6. M-commerce usage scenario

M-commerce applications include mobile ticketing, mobile coupons, information services, fleet-tracking, etc using handheld devices through wireless network access. All these applications require ubiquitous internet access; however this is quite expensive today for ordinary people. One of the main advantages of mesh networks is that they can provide ubiquitous Internet access at a reduced cost and foster the wider deployment and usage of m-commerce applications.

The user requirements are security and privacy, confidentiality, anonymity and integrity of payment messages, as well as the content of the m-commerce services. The network requirements include efficient and scalable QoS support including prioritization, controlled jitter and latency and improved loss packets behavior for multimedia traffic. The existence of mechanisms for secure and fast handoffs between heterogeneous networks and different operators during a transaction and the support of (automatic) re-authentication during handovers is also required.

6. Technical Requirements

This section considers the high level requirements in addition to the network and service provider requirements, and identifies the specific technical requirements and functionalities that multi-operator based QoS aware mesh network must support in order to fulfill them. Tables 2 and 3 summarize the high level user/application requirements and the Network/service provider requirements respectively.

6.1. Cross-layer performance monitoring

To support QoS while efficiently utilizing network resources, it is required to develop a cross-layer architecture enabling measurement-based monitoring of relevant performance parameters across layer boundaries. This approach is based on the idea that every layer must cooperate to gather better results in terms of throughput, power consumption, routing, mobility support, etc. This cooperation can include joining of layers to super layers, inserting new layers with/without changing the primitives used in the old layers, and interaction between non-adjacent layers

[12]. These changes make cross-layer design different from that for a layered architecture.

A recent trend in the literature is to use a parallel layer which interacts with all the layers. This layer is called as “Optimizer Block” [13], “Shared Database” [12], “Network Status Component” [14], and “State Manager” [15] by different researchers. But the main idea is the same: “Let layers share information via a layer which can be interacted by all the layers. The OLD style of interaction between the layers must be preserved.”

The main question here is “what/how information must be stored and shared within a cross-layer design principle?” [16, 17] list some possible interactions between the layers. We list 5 important points that must be considered when designing cross-layer solutions:

Scope of the exchanged information in cross-layer solution.

Access rights of the layers on the stored information - The access rights will ensure to avoid unstable control loops between the layers.

Adaptation to current Management Information Base (MIB) approaches to store and retrieve the information.

Possibilities of measurements of the *metrics* – In this context, *how* to measure a metric is as important as choosing *what* to measure.

Table 2. User/application requirements

High-level user and application requirements	Technical requirements and functionalities
QoS	End-to-end QoS mechanisms to support the service and application QoS requirements
High and symmetric uplink and downlink speeds	Efficient utilization of the aggregate backhaul gateway capacity, from both provider high-capacity links and subscriber broadband access lines
Seamless mobility	Fast, reliable, and secure handoffs supporting QoS in multi-operator environments Minimization of handover time to satisfy application specific delay bounds (e.g., <50 ms for VoIP) Ubiquitous coverage
Low cost, affordability	Efficient utilization of wireless and wired resources, and minimization of interference
Reliability	Exploitation of path redundancy and self-healing procedures
Security	Authentication and access control for mesh clients: Protection of wireless communications: Increasing the robustness of the networking mechanisms: (especially the routing and the transport protocols): Intrusion detection and recovery:
Availability	Ubiquitous coverage, Self-healing procedures
Location-based services	Position and presence information
Operation friendliness/ease-of-use	Service discovery and service availability Seamless service delivery Self-configuration
Full range of services-one contract	Integrated fixed, nomadic, and mobile services

Metrics for different network technologies - Bytes, packets, power levels, etc can be used as measurement

metrics. The proposed architecture includes heterogeneous network technologies. Thus, metrics must be chosen carefully.

6.2. Seamless mobility

Global mobility is achieved when both seamless vertical (among different types of networks) and horizontal (among networks of the same type) handovers between different domains (inter-domain handoff or macro-mobility) or inside the same domain (intra-domain handoff or micro-mobility) are supported.

Handover is a process that involves a delay and the two main components that contribute to its value are the discovery and the re-authentication procedures. The discovery phase, performed by a scanning, is triggered by the degradation of some physical parameters (like the signal-to-noise-ratio or the signal-strength) and determines a list of new networks to which to associate. The re-authentication step involves both authentication and association to the new selected network.

Table 3. Network/Service Provider requirements

Network and service provider requirements	Technical requirements and functionalities
Low-cost and fast infrastructure deployment	Fast and efficient self-configuration procedures
Low operation and management cost	Efficient utilization of wireless and wired resources
Flexibility and scalability	Fast and efficient self-configuration procedures Efficient utilization of wireless and wired resources, and minimization of interference
High and symmetric downlink/uplink speeds	Efficient utilization of wireless and wired resources, and minimization of interference
Service to both fixed and mobile	Converged wireless and wired infrastructure Seamless handoff
QoS and SLA support	End-to-end QoS and service/policy differentiation mechanisms Real-time monitoring of performance and available network resources, based on standard interfaces Fast and accurate identification of anomalies and security attacks
Seamless mobility	Fast, reliable, and secure handoffs supporting QoS in multi-operator environments Minimization of handover time to satisfy application specific delay bounds (e.g., <50 ms for VoIP) Ubiquitous coverage
Reliability and security	Exploitation of path redundancy and self-healing procedures Proactive and reactive security procedures Fast and accurate identification of anomalies and security attacks
Availability	Ubiquitous coverage Self-healing procedures Real-time monitoring of performance and available network resources, based on standard interfaces

Supporting of heterogeneous applications and user's demands, global mobility solutions need to support backward compatibility with legacy systems and current standards and adaptability of the handoff schema to the different delay bounds of each

application. Fast handoff between heterogeneous networks and different operators involves reducing the two components (scanning and re-authentication) that contribute to the overall delay. This can be achieved by considering application layer solutions that do not introduce network overhead, and ensure portability and platform independency. Furthermore methods proposed should self-tune and self-optimize a list of internal parameters that control the handoff procedure when the network's context changes (e.g., connectivity disruption).

6.3. Proactive/Reactive Security

It is evident that in order to support business transactions by deploying wireless mesh networks and providing Internet access and other services to customers, one needs to consider security issues seriously and address them appropriately. The reason is that it is relatively easy to carry out various attacks against mesh networks due to the wireless nature of the communication medium, and due to the lack of physical protection of the unattended mesh nodes. Furthermore, if security is not handled appropriately, then customers may prefer alternative technologies; this would hinder the adoption and wide-spread deployment of mesh networks, which in turn, would result in loss of business opportunities.

The security requirements that are relevant for wireless mesh networks in general, and for QoS aware multi-operator based mesh networks in particular, can be found in detail in [18]. We identify that some applications running on top of a mesh network may have highly application specific security requirements; we are not particularly interested in those requirements though, as they are difficult to identify without the specification of the application itself.

7. QoS Requirements

Quality of Service (QoS) support is of central importance for broadband wireless access systems. Intuitively, the goal of QoS is to provide statistical guarantees on the ability of the network to deliver predictable performance. More precisely, users' needs and preferences, together with application characteristics, form the set of application requirements demanded to the network services and protocols. Then, application requirements are translated into a set of qualitative and quantitative features that the network should guarantee. The system qualities that form the basis for the QoS requirements are several and include:

Performance – The set of system parameters used to quantitatively assess the application behaviour.

Metrics that are commonly used are the desired application data throughput, the maximum end-to-end (from source to destination) delay for data packets, the delay variability, and the maximum packet loss rate.

Availability – A measure of how often the system resources and services are accessible to end-users.

Scalability – The ability to add capacity to the system over time, so that the system can support additional load from existing users or from an increased number of users.

Several approaches have been investigated to provide QoS support in wired networks, such as routing enhancements (e.g., MPLS), advanced resource reservation protocols (e.g., IntServ), or traffic differentiation and prioritization (e.g., DiffServ). However over-provisioning of bandwidth and network resources still remains the most common solution for QoS management in wired networks.

The problem of providing QoS support in wireless networks is even more challenging than wired networks due to the unique characteristics of the wireless medium. Specifically, the wireless channel is intrinsically unreliable and time varying, and subject to interference, multipath propagations, and burst channel errors, which make the bandwidth a precious and limited resource. In addition, although multi-hop communications are beneficial to improve network reliability and extend network coverage, they may also lead to severe performance degradations as the number of relaying nodes increases. For these reasons, in order to provide an effective QoS support in mesh networks, it is of paramount importance to design novel QoS models to ensure an efficient utilization of the available wireless resources, to improve the network capacity, and to increase the backbone scalability.

To address the above technical challenges a multi-operator based QoS aware mesh network should employ a multifaceted approach. Firstly, it should utilize multi-radio and multi-channel capabilities, as well as directional antennas, to build the mesh network, which can enhance spectrum reuse and capacity by promoting channel diversity. Moreover, a multi-radio and multi-channel environment is more likely to experience path diversity, i.e., the existence of multiple paths between a pair of nodes that are independent in terms of interference and congestion, which is generally beneficial to provide more effective QoS support. Another strategy to deal with the capacity limitations of typical broadband wireless access systems, is to fully integrate into the mesh backbone all the available fixed access technologies, namely both provider fixed broadband links like 802.16 BWA and fibre links and subscribers access lines like ADSL. In this way, the mesh network capacity towards the Internet will not be restricted only to a few provider-

owned Internet gateway connections, but it will consist of the aggregate capacity of subscriber access lines, which are now isolated and typically underused. Thus, the converged mesh infrastructure can offer a virtual pool of communication resources to both local stationary users and remote mobile users.

Building ultra-high capacity mesh networks opens up new avenues for optimized QoS support and more efficient network resource utilization, as well as new technical challenges. Specifically, to unleash the potential of the multi-user diversity that is provided by the use of multi-channel technologies, multi-radio capabilities and directional antennas it is necessary to design efficient policies to coordinate the use of the wireless and wired network resources. It is of paramount importance to understand the interactions of the various wireless control mechanisms, such as channel assignment, power control, coverage control through beacon power control, and channel mechanisms (e.g., 802.11e, 802.11n), and quantify how each influences the overall performance. Such understanding will help to investigate joint procedures to optimize the wireless resource utilization. It is also intuitive to observe that the enforcement of QoS constraints cannot be achieved without considering the interdependencies existing between topology formation, channel assignment and routing. For instance, QoS-aware routing capable of discovering feasible paths that satisfy QoS constraints needs to take into account not only topology information, but also channel characteristics (i.e., channel allocation, link capacity, packet loss ratio, and interference), as well as traffic dynamics and distributions.

8. Conclusions

The trend in the development of wireless mesh networks is to utilize multi-radio and multi-channel capabilities which, combined with QoS support, can provide ubiquitous and ultra-high speed broadband access. The supporting network architecture could be based on a converged infrastructure that uses a wireless mesh network to aggregate the capacity from both subscriber broadband access lines and provider fixed broadband links to form a virtual capacity pool, and provide access to this capacity pool for both stationary and mobile users. It could maintain low operation and management costs, through novel configuration and management procedures that achieve efficient use of both the wireless spectrum and the fixed broadband access lines. This approach could increase the competitiveness of existing operators, lower the barrier for small enterprises to enter the mobile broadband access market, and enable innovative services.

Existing solutions for building wireless mesh networks suffer from reduced spectrum efficiency and high interference due to lack of effective power/channel control algorithms, lack of reliable self-configuration procedures that can dynamically adapt to varying network conditions, lack of efficient and scalable end-to-end QoS support, lack of generalized and seamless mobility support, and lack of a comprehensive security solution.

This paper provides a first step towards defining a QoS aware mesh architecture by identifying the user classes, the usage scenarios and the application scenarios that demonstrate the social and economical benefit of a multi-operator based QoS aware mesh architecture and by defining the set of necessary functionalities that such a system should support to fulfill the application requirements.

Next steps towards the development of this architecture include the definition of the complete network and protocol architecture of the proposed mesh system, with the communication interfaces among different service components and protocols, the coordination of vertical issues, and the interfaces for cross-layer interactions.

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