SCUBA: Focus and Context for Real-Time Mesh Network Health Diagnosis

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Abstract. Large-scale wireless metro-mesh networks consisting of hundreds of routers and thousands of clients suffer from a plethora of performance problems. The sheer scale of such networks, the abundance of performance metrics, and the absence of effective tools can quickly overwhelm a network operators' ability to diagnose these problems. As a solution, we present *SCUBA*, an interactive *focus and context* visualization framework for metro-mesh health diagnosis. SCUBA places performance metrics into multiple tiers or *contexts*, and displays only the topmost context by default to reduce screen clutter and to provide a broad contextual overview of network performance. A network operator can interactively focus on problem regions and zoom to progressively reveal more detailed contexts only in the focal region. We describe SCUBA's contexts and its *planar* and *hyperbolic* views of a nearly 500 node mesh to demonstrate how it eases and expedites health diagnosis. Further, we implement SCUBA on a 15-node testbed, demonstrate its ability to diagnose a problem within a sample scenario, and discuss its deployment challenges in a larger mesh. Our work leads to several future research directions on focus and context visualization and efficient metrics collection for fast and efficient mesh network health diagnosis[1].

Keywords: wireless mesh networks, network visualization, network health.

1 Introduction

Metro-scale wireless mesh networks (WMNs)[2], consisting of hundreds of routers, are being deployed worldwide in city downtowns, malls, and residential areas[3]. While several millions of dollars have been spent to deploy WMNs, these networks suffer from a plethora of problems that severely impact their performance. Some of the most common problems are weak client connectivity due to signal attenuation, interference from external devices, and misbehaving or misconfigured client nodes [1]. These problems have largely been responsible for WMN vendors not achieving sustainable client market penetration, thereby leading to dwindling business prospects for this technology.

We believe that the effective diagnosis and troubleshooting of performance problems is key to the success of metro-scale WMNs. Although many novel metrics and techniques to diagnose and troubleshoot problems in WMNs have been proposed by

[1] A video demo of SCUBA is at http://moment.cs.ucsb.edu/conan/scuba/
[2] http://www.muniwifi.org/
[3] www.tropos.com,www.firetide.com,www.strixsystems.com,www.meraki.com

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the research community [9,6], sifting through a sea of such metrics collected from each device in a metro-scale WMN can be overwhelming for network operators.

As a solution, diagnostic tools utilize visualization techniques such as time-series plots and planar graphs[4]. However, the diagnosis of problems by viewing a myriad of such graphs and plots in large-scale WMNs can be very tedious and time-consuming. We believe that operators of large-scale WMNs need clever *structured* visualization techniques to quickly navigate through metrics and diagnose problems. Numerous publications have shown that good visualizations decrease the time and effort to evaluate large volumes of information in the Internet [11,10,8][5]. To our knowledge, diagnostic visualizations of large-scale WMNs have received little to no research attention yet. In this paper we argue that these networks can certainly benefit from visualization tools, especially due to their increasing sizes and complexities.

To this end, we propose a *focus and context* visualization framework named *SCUBA*[6]. SCUBA places performance metrics into several tiers or *contexts*. The topmost context provides a WMN operator with a broad contextual overview of WMN performance. By viewing only this broad context, WMN operators can quickly identify and locate problems within the WMN. Once a problem location is determined, an operator can choose to narrow his/her focus on the problem region and zoom to reveal detailed metric contexts within that region. In other words, the operator exposes a larger set of metrics within a small focal region to diagnose the cause of a performance problem.

In this paper we propose a scheme for organizing metrics into three contexts (route, link, and client) with increasing detail. The placement of metrics is based on our experience of diagnosing WMN problems [5]. However, the main objective of SCUBA is to *facilitate* focus and context visualization for any scheme. Different schemes derived from WMN operators' common diagnostic approaches will be explored in the future to define better contexts as well as better placement of metrics within contexts.

To explain contexts, metrics, and views of SCUBA, we utilize the Google Mountain View WMN map of about 500 routers and gateways[7]. To understand SCUBA's ease of use in diagnosing a sample performance problem and it deployment challenges, we implement it on the 15-node UCSB MeshNet [5].

2 *SCUBA*: Focus and Context Visualizations

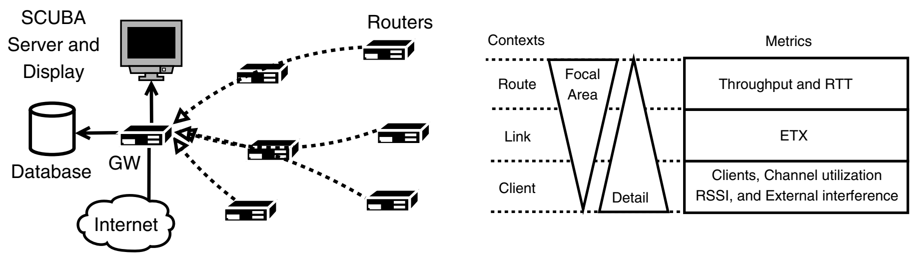
The main objective of SCUBA is to facilitate fast and easy diagnosis of WMN performance problems by cleverly organizing the performance metrics for focus and context visualizations. In this section we discuss the metrics collection architecture, the organization of metrics into contexts, the different views SCUBA offers to the operator, and the variety of visualization features implemented in SCUBA.

[4] NetCrunch: http://www.adremsoft.com/netcrunch/index.php

[5] CAIDA tools: http://www.caida.org/tools/visualization; NetDisco: http://www.netdisco.org

[6] The name SCUBA comes from the sport of scuba diving, where a diver swims close to the water surface and dives deeper to get a closer look at what is beneath the surface.

[7] http://wifi.google.com/city/mv/apmap.html



(a) SCUBA's metric collection architecture. (b) Metric contexts used in this work.

Fig. 1. SCUBA's metrics collection architecture and metric contexts

2.1 Metrics Collection Architecture

The performance metrics visualized by SCUBA are collected and computed from the routers and gateways in a WMN. As shown in Figure 1(a), each router sends a set of metrics to the SCUBA server via the gateway. The SCUBA server stores these metrics in two locations: a database so that temporal trends of metrics can be observed, and a data structure within main memory for fast access by SCUBA's visualization engine. The SCUBA visualization engine is a standalone Java application written using the Swing GUI toolkit. We discuss the computation and collection of metrics specifically within the UCSB MeshNet in Section 3.

2.2 SCUBA's Contexts

One of the main obstacles to diagnosing problems in WMNs today is their sheer scale and the abundance of performance metrics that can be overwhelming to the WMN operator and unrealistic to analyze within a short period of time. To better organize the collected information, we propose that WMN performance metrics be placed into several *contexts*, where each context consists of one or more metrics.

The topmost context provides the WMN operator with a holistic view, a broad contextual overview of WMN health. In other words, a WMN operator can quickly identify both the occurrence and the location of a problem in the WMN from such a broad context. An operator can then use SCUBA to *focus* on specific problem areas. Once the operator shifts focus, he/she can interactively zoom to view more detailed contexts. In other words, the operator can choose to reveal more metrics and therefore increase information detail *isolated within the focal area*.

For the scope of this paper, we place WMN metrics within three contexts; the *route*, *link*, and *client* contexts. These three contexts and their metrics are summarized in Figure 1(b). The figure shows that as information detail increases, the focal region is narrowed in the lower SCUBA contexts. We next describe the organization of metrics in the three contexts and explain how these metrics help isolate causes of a sample WMN performance problem.

Route Context: The route context is the topmost context and only displays multi-hop routes between each router and its corresponding Internet gateway. The context consists of two metrics: (a) throughput of TCP flows over the multi-hop routes formed from each router; and (b) the round-trip time (RTT) of UDP packets on the same routes. The two metrics are computed by each router and determine the quality of the route between the router and its gateway. We include these metrics in the topmost context of SCUBA because any significant drop in their values indicates a serious performance problem. WMN operators can use this problem indication and then zoom into the problem region to understand the real cause of a problem. For instance, problems such as sudden route flaps, unexpected drop in throughput, or an increase in RTT values can cause a performance deterioration of TCP or UDP application flows that utilize those routes. Operators can further investigate the cause of such problems by increasing the context in the problem areas.

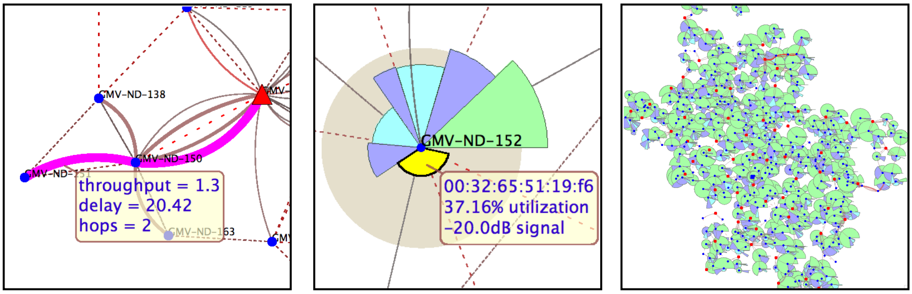
Link Context: The link context reveals one additional metric, the expected transmissions count (ETX) [3] on a link between the nodes. In the link context, SCUBA displays the point-to-point MAC-layer links between nodes in addition to the routes from the route context. We use ETX as a metric in this context because it provides a good estimate of the health of links between nodes. The quality of links is likely to impact the routes that utilize them. As a result, if sudden route flaps or a significant drop in throughput are observed at the route context, the most likely cause is poor quality links utilized by the routes. Poor link quality is identified by an increase in the ETX value at the link context, and typically occurs due to three reasons: (a) heavy volume of traffic flowing over the link and/or neighboring links within its interference region; (b) external interference from a co-located radio wave source that does not belong to the WMN; and (c) heavy signal attenuation caused by some obstacle. Isolation of the causes of poor links is achieved by zooming to the next lower context.

Client Context: The client context provides further insight into the cause of poor quality links. SCUBA includes four metrics within this context: (a) the number of clients associated with each router; (b) the percentage channel utilization per client [4]; (c) the received signal strength indicator (RSSI) of MAC-layer frames received from clients; and (d) the volume of external interference. These metrics are included within this context because they each describe client connections and traffic within a WMN. In the client context, SCUBA displays the clients associated with the routers, along with the links and the routes from the link context. A WMN operator will likely zoom to the client context only when the cause of problems cannot be easily determined at the link context. For instance, the cause of poor link quality can be isolated to either a large number of clients with high channel utilization values or external interference[8]. Both these causes can be determined from metrics in the client context. If neither have adversely impacted the quality of links, the WMN operator can determine that heavy signal attenuation by an obstacle is the likely cause of poor quality links, by the process of elimination.

2.3 Diagnostic Approaches and the Design of SCUBA

The three contexts and the placement of metrics within the contexts we present for the current version of SCUBA have been designed based on our own experience of

[8] We compute external interference as the percentage of channel utilized by transmitters that are not associated with a router.



(a) Route throughput, RTT and link ETX. (b) Client channel utilization and signal strengths. (c) Google WMN, without SCUBA's focus and context.

Fig. 2. SCUBA's visualization features and an example WMN without focus and context

building and deploying a WMN [5], and diagnosing problems using a logical *top-to-bottom* approach. In the future, we plan to evaluate additional contexts such as *traffic* and *application*, for increased diagnosis flexibility in specific application settings. While our scheme is sufficiently general for diagnosing a wide variety of problems [1], it does not represent an all-inclusive set of metrics or the only scheme of context organization. WMN operators may follow alternative diagnostic approaches in different deployment scenarios, and the metrics they may find useful in each scenario can also vary. SCUBA, as a visualization framework, can be modified to utilize different schemes based on the diagnostic approaches preferred by operators. The effectiveness of SCUBA should then be evaluated qualitatively and quantitatively in specific scenarios, using metrics such as its ease of use, how quickly it can help diagnose a problem, and how many problems of interest it helps diagnose. Exploring other diagnostic approaches and evaluating their effectiveness, while outside of the scope of this paper, is part of our usability-oriented ongoing work.

2.4 SCUBA Visualization Features

In this section we discuss the visualization features we use to communicate WMN health using the seven metrics discussed in the previous section. We use different color and size schemes for these features with a single consistent visualization policy across all contexts and metrics, which is to *highlight problems* in the WMN, resulting in fast and easy diagnosis of WMN problems. SCUBA's visualizations are interactive, allowing for continuous pan and zoom and tool-tip-style data readouts on mouse-over and selection. The visualization features, as illustrated in Figure 2, are as follows:

WMN Nodes: We assume that a typical WMN backbone consists of two types of nodes: routers and Internet gateways. SCUBA displays routers as blue circles and gateways as more salient red triangles, as shown in Figure 2 and 3.

Routes: WMN routers relay client packets destined for the Internet via other routers towards a gateway. The gateways relay packets destined for WMN clients towards the router with which they are associated. SCUBA visualizes the routes between routers and gateways as curved solid lines, as illustrated in Figure 2(a). In order to implement our policy of highlighting problems, the thickness of the lines is directly proportional to the RTT value; the higher the RTT, the thicker the line. On the other hand, the saturation and brightness levels of the line is inversely proportional to the throughput on an exponential scale using the HSB color scheme; low throughput routes appear bright red, while higher throughput routes are de-emphasized with a grey color. We also experimented with a more conventional mapping of throughput to line thickness, which might be preferable for non-troubleshooting monitoring applications, but the presented scheme is advantageous when high salience of trouble spots is important.

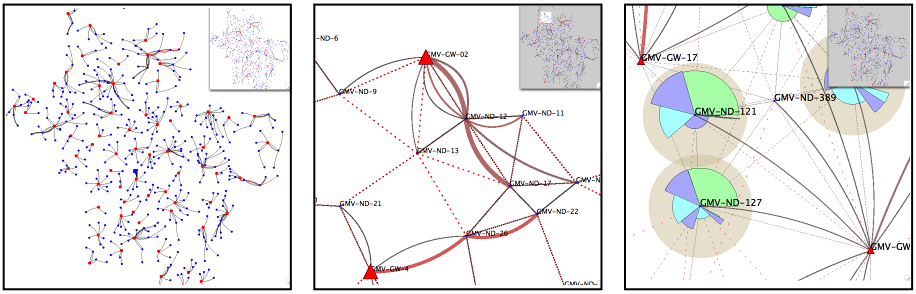
Links: MAC-layer links between nodes are visualized at the link context. The links are visualized as dashed lines, as illustrated in Figure 2(a). To maintain our policy of highlighting problems, the length of white spaces between dashes are directly proportional to the ETX value; higher the ETX value, longer are the white spaces, the more *broken* the links appear. In order to make up for the reduction in saliency by the increasing gap sizes, the thickness of the dashed lines are increased proportional to the ETX value. This visualization feature ensures that the operators' attention is drawn to poor quality broken links, and less towards good quality links represented as thin solid lines.

Clients: The client context of SCUBA shows clients and four related metrics. These metrics are illustrated in Figure 2(b). In this figure, the clients are placed around the router with which they are associated, and are visualized as sectors of a circle. The subtended angle of the client's sector is a value between 0° and 360°, proportional to the client's percentage channel utilization share. As a result, a router with client sectors that form a complete circle has its entire (100%) channel utilized by client frame transmissions. The radius of each client sector is inversely proportional to the RSSI value of the client's frames received by the router. As a result, the lower the client's RSSI, the farther the client is placed from the router, and the larger the radius. Based on these two visualization features of client sectors, a client with a large sector angle and large radius is quickly seen as a potential problem because of high channel utilization and low RSSI. The client with the largest sector area is highlighted in a bright green color, making it easy for a WMN operator to locate all problem clients at the client context. The fourth metric, external interference, is visualized as a grey cloud around routers, as shown in Figure 2(c). The radius of the cloud is directly proportional to the volume of external interference. Moreover, when the interference cloud of two or more routers overlap, SCUBA darkens the color in the region of overlap, indicating more interference.

2.5 SCUBA Views

In this section, we discuss two views of SCUBA, *planar* and *hyperbolic*. These views further ease the diagnosis of problems in large-scale WMNs by facilitating *focus and context* interaction [2] of the WMN operator with SCUBA's contexts. In other words, using either of the two views operators can choose to focus on a specific location in the view while retaining some kind of overview of the whole network, and they can zoom to a context of their choice for further investigation of problems.

To understand the benefit of these views, we use the Google WMN in Mountain View, California, which consists of 425 routers and 66 gateways. Since we do not have access to the actual metrics from this WMN, we use the geo-locations of the routers



(a) Route context. (b) Link context. (c) Client context.

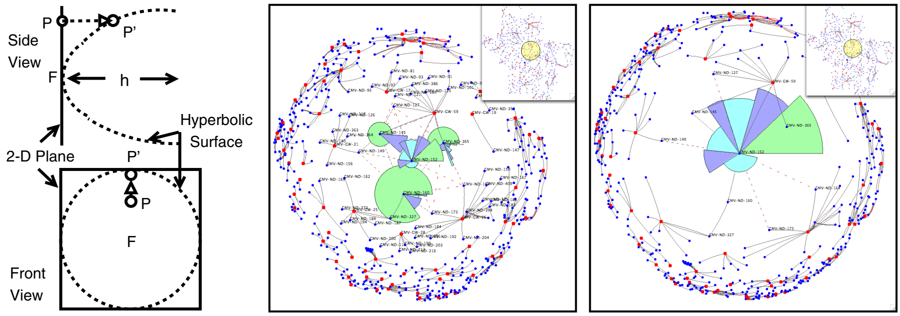
Fig. 3. Google WiFi mesh network using SCUBA's planar view

to create a sample large-scale visualization environment and synthetically generate values for metrics using simple assumptions. Links between routers and their corresponding ETX values are generated in loose correlation with the physical distances between routers. Routes are computed using a shortest path algorithm between the routers and their closest gateways. The throughput and RTT values are computed based on cumulative ETX values of links utilized by the routes to the gateway. Zero or more clients are matched with routers, such that their total count loosely approximates those published in a recent news article presenting statistics on the Google WMN [1]. The channel utilization, signal strength, and external interference metrics are randomly chosen from a uniform distribution.

To clearly demonstrate the advantages of the focus and context visualizations of SCUBA, in Figure 2(c) we show a screenshot of all seven metrics from each of the three contexts displayed for the Google WMN. Because of the size of network, the screenshot appears cluttered, thereby limiting the ability of an operator to extract any coherent information from the view for problem diagnosis. We now discuss the two interactive SCUBA views, how they reduce screen clutter, their advantages over each other, as well as their trade-offs.

Planar View: SCUBA's planar view is shown in Figure 3. The WMN and its several contexts are rendered on a flat two-dimensional plane. Figure 3(a) shows the planar view with only the route context displayed for the entire Google WMN. Figure 3(b) shows the link context of a small subset of the network, when the WMN operator zooms to investigate any performance problems identified at the route context. These figures also show an *inset overview* in the top-right corner that indicates the focal region in the overall view. Further zooming reveals the client context, illustrated in Figure 3(c). The focus region in the overview inset is seen to shrink in size, because the operator is now zoomed to a smaller focus region.

The advantage of SCUBA's planar view is that it maintains the geographical location and orientation of all the routers and gateways, even while an operator changes focus and context. However, the trade-off of planar views is that while operators are zoomed in on lower metric contexts, they can only see the small inset overview of the whole



(a) Side and front views. (b) With $h = 1$. (c) With $h = 50$.

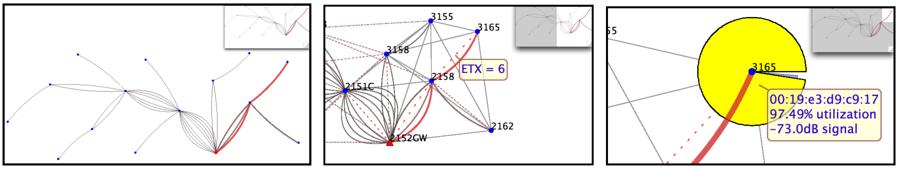
Fig. 4. Google WiFi mesh network using SCUBA's hyperbolic view

network, which may not be sufficient to alert them to possible new unusual activity. We overcome this problem by using *hyperbolic* views [7].

Hyperbolic View: SCUBA uses the hyperbolic view to render routers, gateways, clients, and their corresponding metrics on a hyperbolic surface [7]. The basic idea of a hyperbolic view is to plot the focal point F of a two-dimensional plane at the center of the screen, and plot the remaining points on a hyperbolic surface, centered at the focal point. Figure 4(a) illustrates the side and front of a hyperbolic surface transformed from a simple two-dimensional planar surface. The figure shows that the non-focal location point P on a two-dimensional plane is distorted to *P'* when transformed to the hyperbolic surface. The distortion depends on the height h of the hyperbola.

The hyperbolic view has an advantage over the planar view in that it *automatically* renders different contexts of SCUBA based on the position of the node with respect to the focal point. As shown in Figure 4(b), the node of interest forms the focal point of the hyperbolic surface and the remaining nodes are rendered on the hyperbolic surface, using the same *orientation* to the focal node as in the planar view. Also, as illustrated in Figure 4(b), SCUBA plots all the metric contexts for the focal node and progressively reduces the contexts for nodes further away from the focal node. As a result, only the route context is displayed for the nodes at the edge of the hyperbolic surface. Figure 4(c) shows that a parameter controls the depth of the hyperbolic surface, which determines how quickly context displays are reduced between the focus node and the surface edge.

A main advantage of the hyperbolic view is that it shows a complete view of the WMN at all times, and automatically changes contexts as the operator interactively changes focus by mouse-dragging. As a result of this automation, the user is required to only choose his/her focus point, and SCUBA smoothly transitions to display the new focal region and the corresponding contexts. However, the trade-off of hyperbolic views is that it distorts the geographic locations of the nodes from that of a planar view. As a result of these trade-offs between the two views, SCUBA includes an inset overview similar to the one used in the planar view and allows a WMN operator to quickly toggle between the planar and hyperbolic views.



(a) Route context shows a drop in route throughput.

(b) Link context shows a poor broken link.

(c) Client context shows a client with 97.49% utilization.

Fig. 5. SCUBA used to diagnose a sample problem in the UCSB MeshNet

3 SCUBA Implementation on the UCSB MeshNet

Our main goal for SCUBA is to make it easily usable and effective in diagnosing practical WMN problems. To test this capability, we have used SCUBA to study the performance of the UCSB MeshNet, an indoor WMN consisting of 14 multi-radio 802.11 a/g routers and one gateway. The routers collect, compute, and send metrics to a central SCUBA server via the gateway over the routes. In this section, we show how SCUBA is used to diagnose a sample performance problem within the MeshNet.

In the route context shown in Figure 5(a), the operator observes the unusually low throughput and high RTT values of a route indicated by the thick red lines. The operator zooms in the region of the route to access the link context. The link context in Figure 5(b) clearly shows that the links utilized by the problem route have a high ETX value, indicated by the sparsely dashed straight lines. To determine the cause, the operator zooms to the client context close to the edge router using the problem route, as shown in Figure 5(c). In this figure, the large sector of the circle representing a client with 97.49% channel utilization looks clearly anomalous. The operator is thus assured that a single misconfigured and/or misbehaving client is overloading the channel with excess traffic and adversely impacting the performance of an entire route.

The current version of SCUBA allows operators to diagnose several other performance problems, such as a flashcrowd of users overloading the network or suboptimal route topologies caused due to poor links or interference. The set of diagnosable problems will increase with the number and type of metrics collected. Moreover, the addition of a *time* dimension will allow SCUBA to diagnose many more temporal problems, such as rapid route flaps and client mobility.

4 Conclusions

In this paper, we propose a focus and context visualization framework called SCUBA for fast and efficient WMN health diagnosis. SCUBA places WMN performance metrics into contexts and presents them in two views, planar and hyperbolic. We believe that visualization frameworks such as SCUBA will form the most structured and efficient means of WMN health diagnosis.

SCUBA opens several new directions of research. The most prominent one is to qualitatively and quantitatively determine the *best* set of metrics and contexts that facilitate comprehensive diagnosis. To do so, we believe that qualitative usability studies of SCUBA's visualization methods and the study of various diagnostic approaches preferred by WMN operators will be very helpful. Another research direction is to reduce the metrics' computation and collection overhead to achieve *real-time* visualization capabilities. A possible future extension is to make SCUBA use a set of diagnostic rules to *automatically* identify problem regions and adjust focus and context accordingly. Such automation will immediately direct an operator's attention to the problem and will likely reduce diagnosis time.

SCUBA is the first step towards interactive visualizations for fast and efficient WMN health diagnosis. We believe that as WMNs are rapidly deployed worldwide and as they increase in complexity, the need for such visualizations will grow. Faster and efficient health diagnosis will help operators maintain their WMN's performance and therefore achieve the desirable economic success of the metro-scale mesh technology.

Acknowledgments

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