DOME: A Diverse Outdoor Mobile Testbed

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ABSTRACT

A series of complex dependencies conspire to make it difficult to model mobile networks, including mobility, channel and radio characteristics, and power consumption. To address these challenges, we have designed and built a testbed for large-scale mobile experimentation, called the Diverse Outdoor Mobile Environment. DOME consists of computer-equipped buses, battery-powered nomadic nodes, organic WiFi APs, and a municipal WiFi mesh network. While the construction of a testbed such as DOME presents a significant engineering challenge, this paper describes a concrete set of scientific results derived from this experience. We argue that a broad range of mobility experiments could be performed in a testbed which provides the properties of temporal, technological, and spatial diversity. We demonstrate these properties in our testbed through analysis of data collected from DOME over a period of four years. Finally, we use DOME to provide insight into several open problems in mobile systems research.

1. INTRODUCTION

Mobile systems and networking researchers confront a myriad of challenges, including power consumption, channel and radio characteristics, mobility, and node density. Moreover, mobile systems span a wide spectrum of rapidly evolving radio technologies (WiFi, Bluetooth, UWB, 3G, GPRS, and 900MHz radios), mobile devices (laptops, PDAs, and music players), and networking paradigms (mobile ad hoc, disruption tolerant, and infrastructure-based networks). Analytical models that consider such complex interactions still may not cover indirect factors such as social trends and real-world distribution of resources. Many of these difficulties are best addressed by evaluations that are based on mobile system testbeds. To support the comparison of a wide array of systems, testbeds must provide spatial, technological, and temporal diversity, realistic mobility patterns, power consumption, latency, throughput, and end-user participation. For instance, measuring how the performance of cellular and organic WiFi have changed over time across urban and rural areas requires a testbed with a broad range of capabilities.

Unfortunately, building a sufficiently general testbed is typically infeasible due to the time and expense required—the majority of existing testbeds are tuned to a particular area of mobility research. For example, while deployments such as Haggle [9] study sparse mobile-to-mobile communication, other testbeds such as CarTel [10] and VanLan [13] study dense vehicle-to-access point (AP) communication over WiFi links. On the other hand, a primary goal of mobile computing research is the ability for systems to transparently move among any of these scenarios. Hence, testbeds for mobile computing research ideally possess both technological and spatial diversity, enabling the evaluation of different radio technologies and network architectures in varied densities.

Another major shortcoming of many existing testbeds is the relatively small time scale of data collection. Many trends in mobile computing take place over longitudinal time scales. For example, a great many projects rely on opportunistic connections to open WiFi APs, yet trends in open AP availability have not been measured. Similarly, the populations and geographic areas of most testbeds are small. Results based on only a few mobile or stationary nodes covering a relatively small area cannot, in general, be extrapolated to more extensive scenarios.

To address these shortcomings, we have designed and deployed an evolving Diverse Outdoor Mobile Environment (DOME). To our knowledge, DOME is the longest-running large-scale, highly diverse mobile systems testbed. The testbed has been operational since 2004 and provides infrastructure for a wide range of mobile computing research. It includes 40 transit buses equipped with computers and a variety of wireless radios, 26 stationary WiFi mesh access points, thousands of organic access points, and half a dozen nomadic relay nodes. It provides support for diverse radio technologies, including WiFi, 900MHz, 3G, and GPRS. It covers an area of 150 square miles and provides spatial diversity; parts of the network form a sparse, disruption-tolerant network while others are more dense. The testbed can support research ranging from infrastructure-based networking to sparse and dense ad hoc networks. Furthermore, it can be used as a valuable infrastructure to collect real-world information about mobile users in various scenarios at a large scale (e.g. carrying different devices in and outside of vehicles).

Our goal in this paper is not to discuss in detail the challenges and problems faced in building DOME. Nor would the space limitation allow us to discuss the lessons we learned in building such a large-scale and diverse testbed. More information about these issues can be found in our technical report [17].

However, this paper describes a concrete set of scientific results derived from this experience not published in our prior

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work. We show the usefulness of DOME by demonstrating how it provides for the properties of temporal, technological, and spatial diversity. Our analysis is based on data collected from DOME over a period of four years. Finally, we use DOME to provide insight into several open problems in mobile systems research.

2. THE CASE FOR DOME

An examination of many current networking testbeds, both wireless and wired [1,7,9–16,18], reveals that most of them are short lived, lack hardware and geographic diversity, cannot be programmed remotely and lack scale. In order to overcome challenges in improving large-scale mobile systems, long-running remotely programmable yet diverse testbeds are needed which can address a number of open and ongoing questions in mobility research:

Challenges related to temporal trends: A large body of recent work is based on the availability of open WiFi access points that provide free, ubiquitous connectivity to mobile users. At the same time, off-the-shelf APs increasingly help less tech-savvy users to restrict access. *Are research systems that use open APs for ubiquitous connectivity viable in the long term?* The answer requires a study of the longitudinal trends in open versus encrypted APs. Similar questions can be asked of research relying on the popularity of peer-to-peer networking connections [9] or ubiquitous cellular deployment.

Challenges related to technological diversity: The use of different radio technologies, such as WiFi, 3G, and proprietary 900 MHz radios among others, presents a fundamental cost-benefit trade-off. Opportunistic connections to open AP WiFi is free but can suffer from disrupted coverage or poor quality. On the other hand, cellular technology like 3G has better coverage but comes at a higher monetary cost. Several fundamental questions are relevant: *What are the performance characteristics of each type of network? Can multiple radios support and complement one another? How does the performance of open free WiFi infrastructure [10] compare to self-deployed mesh nodes [7,11]?*

Challenges related to spatial diversity: The performance of many network scenarios is dependent on spatial density of infrastructure or peers, spanning issues of coverage, mobility, and interference. Observations about spatial diversity in the field can help address questions such as, *For what densities are MANETs or DTNs practical [5]? Similarly, at what density are infrastructure networks sufficient to support delay-intolerant applications [2]?*

Some of these questions have been answered in isolation, on a small scale, or for short periods of time; however, there is a need to answer these questions on a continuous basis, confirming trends or discovering new ones, and evaluating systems over longer time scales, wider geographic regions, and through heterogeneous hardware living under a common testbed. We have constructed and evolved DOME to help address these challenges. However, it is important to note that DOME does not, and cannot answer, all of these questions at present. Rather the intention of DOME is to answer a large number of questions and remain an evolving platform to be able to answer more of them.

3. IMPLEMENTATION OF DOME

To give other testbed designers a starting point, and to place our traces and evaluation in context, here we provide an overview of the hardware and software that comprises DOME.

3.1 Hardware Components

The DOME testbed consists of three major hardware components: the DieselNet vehicular network, a set of nomadic throwboxes, and an outdoor mesh network. At various times since DOME's inception, we have upgraded or improved virtually every hardware and software component. This has created unique challenges for extracting longitudinal data, as we discuss in Section 4.

DieselNet Vehicular Nodes: Mobility in DOME is provided by a vehicular network called DieselNet [6]. It provides nodes that operate year-round, across a micro-urban and rural environment covering an area of 150 sq. miles. While parts of the network forms a sparse DTN, other areas see mobile nodes clustered together for long periods of time. DieselNet is comprised of 40 transit buses each equipped with Hacom OpenBrick 1GHz Intel Celeron M systems (referred to as *bricks*), a GPS receiver, 802.11abg mini PCI cards (upgraded from 802.11b USB WiFi dongles), 802.11g wireless access point, Wireless 3G USB modems (upgraded from a GPRS modem), and 900MHz USB RF modem. Further details appear in our technical report [17].

A brick's access point allows other buses, or bus riders, to establish 802.11 connections into the brick, giving them access to the Internet via the 3G modem. The WiFi interface is used by a brick to connect to foreign access points, including the APs on other buses.

Throwboxes: Throwboxes are wireless nodes that can act as relays, creating additional contact opportunities among DieselNet buses [4]. They are nomadic nodes allowing for flexible placement in the DOME testbed. Unlike the vehicular nodes, the throwboxes use batteries recharged by solar cells. Also in contrast to the vehicular nodes, a throwbox will often remain stationary for several hours or days. The boxes attach to the front of bicycles, which gives us the ability to easily reconfigure nodes in the testbed to support different placements and functions. We have demonstrated the usefulness of Throwboxes in enhancing network accessibility in [4].

Mesh Network: 26 lightweight Cisco 1500-series WiFi access points have been mounted on different buildings and light poles of our town, supporting seamless hand-offs and managed by a central controller. While both locations provide power, only the buildings provide connectivity to the local fiber infrastructure. Consistent with research findings [7] and Cisco's instructions, the network is laid out such that there are never more than three hops to the wired network. A Procera PacketLogic box yields statistics about users, node mobility, and traffic patterns.

3.2 Software Components

Link Management Module: We have implemented a software module called *LiveIP* that scans for SSIDs, establishes and maintains WiFi connections as defined by the policies set by the currently executing experiments, and notifies applications of the state of the WiFi link. The LiveIP configuration allows us to define regular expressions for prioritized and blacklisted SSIDs, as well as the policy for dropping an association. We can tailor the policy to individual experiments, e.g., to connect to only public APs.

Remote Update Mechanism: Nodes periodically check the DOME server via WiFi and 3G for updates to their software or configuration. We have no control over when a system shuts down; a brick simply loses power when the bus's engine is turned off. A concern is losing power during a critical section of an update, which can render the brick unusable until we are able to physically access it and make manual repairs. We use a shadowing approach, isolating a copy of the software update and preserving atomicity by modifying a single symbolic link.

Logging: We have provided common logging services to collect a variety of traces from logs of contacts between elements in the testbed, GPS coordinates of contact locations, and throughput logs for different radio technologies used on the mobile nodes to the connectivity status of the radios at different geographical locations.

Maintenance Monitoring: A monitoring service allows us to track the health of the testbed and know how many nodes are operational and which peripherals are malfunctioning. Even if components fail, the DieselNet monitoring software will attempt to establish connectivity to the DOME servers to provide notification. We also correlate vehicular node activity with the bus schedules, allowing us to detect nodes that have errors.

4. RESULTS AND INSIGHTS

DOME uses a variety of radio technologies and hardware components and has been in continuous operation since 2004. These features demonstrate its technological and temporal diversity. DOME also proves to be a spatially diverse testbed providing regions that are well-connected to the infrastructure, as well as regions that are poorly connected. Hence, with proper isolation the traces collected from the testbed can be used for research in sparse and dense mobile networks. Details of the experiment demonstrating DOME's spatial diversity can be found in our technical report [17]. In this section, we use traces from DOME to provide insights into a subset of open questions discussed in Section 2.

4.1 Trace Evaluation Methodology

The DOME testbed has collected numerous mobility and connectivity traces since 2004 that we have used to derive the results in this section. The most crucial of these logs is a list of contacts among vehicles, as well as between vehicles and the infrastructure. Logs include duration, GPS location, and speed at the beginning and end of every contact. Since September 2007, the nodes have also collected the number of APs seen in each scan, as well as what portion of those employ some form of access restriction. Also since September 2007, the vehicles have collected additional information about contact with APs, including successful associations and DHCP leases. During short term tests, we have deployed measurement apparatus to measure the fraction of time a node spends connected to a cellular network (GPRS and 3G) and connected to WiFi APs.

We have been able to answer many questions posed in Section 2 using data originally collected for markedly different purposes. In other cases, we have deployed short-term experiments for additional clarification in this paper. In all cases, we have removed the effects of the varying number of vehicles operating, such as summers and vacations, which have a much reduced bus schedule, and aberrant vehicle behavior, such as temporary use of a bus for a field trip. For experiments that depend on different regions of the network if there are less than 30 visits to a region during a month, we discard all measurements from that region, and normalize the results based on the number of remaining regions. Given the scale of the testbed—there are often 30 or more buses operating 18 hours per day—-the testbed has yielded an enormous amount of data. Since 2004, we have recorded 8,679,179 contact attempts between our vehicles and

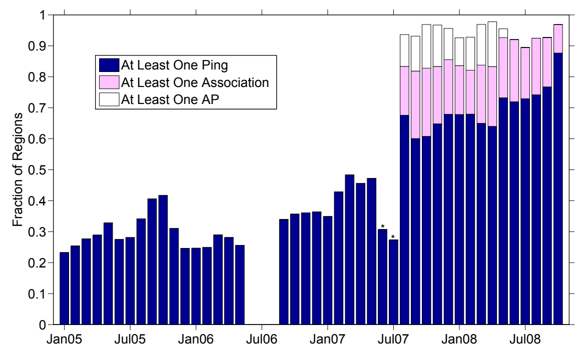

Figure 1: The number of regions that supported at least one successful ping through vehicular WiFi during a month. Summer 2006 is omitted due to software problems. Access to both campus and town WiFi networks began in summer 2007. From September 2007 on, we show which regions supported at least one association or a scan with at least one AP (but not a successful ping).

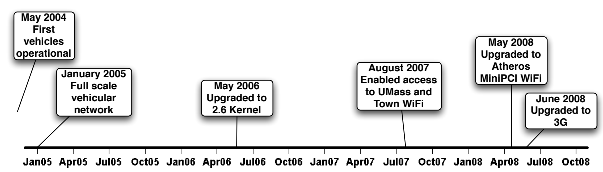

Figure 2: The timing of significant hardware and software changes made to the DOME testbed.

28,776 unique APs; of those attempts, 2,110,595 were successful. During that time 1,091,307 successful contacts between vehicles occurred.

4.2 Trends in Availability of Organic WiFi

A number of research projects have proposed the use of organic, open WiFi APs for opportunistic networking, particularly for vehicular networks [3, 8, 10]. A fundamental research question facing this community is whether coverage has improved along with an increase in the number of deployed APs, given that additional APs may have been secured or deployed in regions where access has already been available. To quantify this trend in our area, we analyzed our traces since January of 2005 to find which 100m $\times$ 100m regions had at least some connectivity, meaning that at least one successful ping was sent to our server during that month from a bus in that region. A plot of that analysis is shown in Figure 1.[1] Measuring the number of regions that have some connectivity is somewhat complicated by several changes that have occurred in our testbed as shown in the time-line in Figure 2. The strength of this data is that it is a longitudinal study over a diverse geographic region (c.f., shorter tests over a more homogeneous set of regions [10]).

From January 2005 to May 2008 we used USB 802.11 interfaces with the Prism2 chipset—these interfaces exhibit range similar to what one might find in a laptop computer. Over the course of January 2005 to May 2006, the vehicles only found connectivity in 20% to 40% of the regions, with no significant trend over the course of that year and a half. This data demon-

[1] The portion of this graph representing regions with at least one ping (i.e., the darker bars) during August 2007 to October 2008 also appears in a paper currently under review.

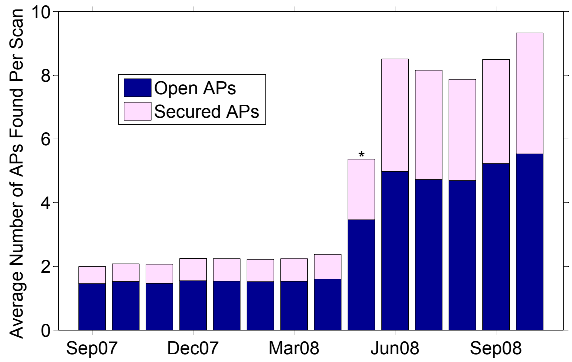

Figure 3: The number of APs found per scan over a 13 month period.Installing more powerful MiniPCI WiFi interfaces increase the overall number of APs in summer 2008.

strates that building a mobile application on top of such a system would have exhibited significant disconnections and outages. During the summer of 2006, we added the first cellular modems but failed to disambiguate connections through the two interfaces, so that data is omitted from the graph. During the fall of 2006, we continued to use USB WiFi devices, and still found that more than 50% of the regions had no WiFi coverage whatsoever, although the increase in use of wireless access points brought coverage to almost double the number of regions that were covered in early 2005.

During the summer of 2007, we installed and enabled access to the town mesh and enabled access to the campus wireless network (both require click-throughs). In September 2007, we began tracking pings, associations, and regions where scans revealed APs, but no connection was possible. In May 2008, we upgraded from USB 802.11 interfaces to Atheros MiniPCI cards with external antennas. This yielded increased range and further improved the number of regions covered. The collection of improvements shows that given the proper hardware in an environment with a combination of managed and open access points connectivity can reach nearly 90% of regions. However, many environments do not have the benefit of a deployed infrastructure and will see much less coverage. **Result 1: Given applications that send relatively short messages, or are insensitive to throughput, organic WiFi will provide sufficient coverage in our environment.**

There has been recent anecdotal speculation that while the use of WiFi is expanding, APs are increasingly protected by encryption. As the previous result shows, encrypted APs have not significantly impacted coverage. But what portion of APs are encrypted and are there any noticeable trends? **Result 2: The increase in total number of deployed APs has not been accompanied by a significant relative decrease in the number of open APs,** as shown in Figure 3. The overall number of APs discovered per scan increases as we upgraded the WiFi interface on the vehicles. However, the increased range also discovered an increased proportion of encrypted APs, but did not show a noticeable trend of open APs disappearing. We speculate that the increased proportion of encrypted APs can be explained by the increased range of the radios capturing more residential APs, as many of the open APs are located in businesses with free WiFi. Overall, It seems that hardware has a more significant effect on the results discussed above comparing to any identifiable trend in the availability of WiFi hotspots.

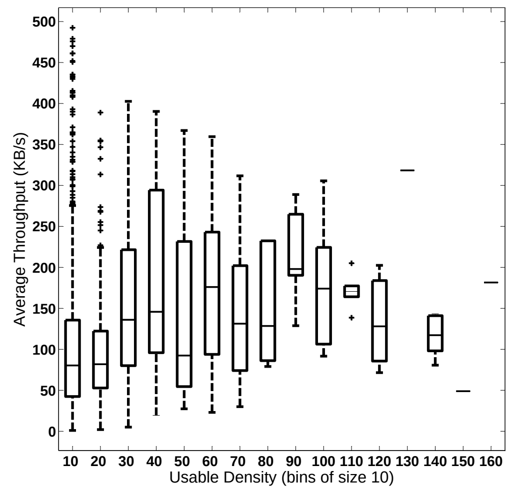

Figure 4: The correlation between WiFi throughput and the density of APs in a region for a period of five months from June 2008 to October 2008. Boxes show first and third quartiles, while the center line shows the median. The whiskers show max and min values, while the stars demonstrate extreme outliers.

4.3 Effects of Density on Throughput

As DOME has collected data from a wide variety of geographic regions, we can also examine the relationship between the density of APs found in a region to the usable throughput between a vehicle and a single access point. Due to the relatively small number of non-interfering channels to choose from, a primary concern in the dense deployment of APs has been the possibility of interference between nodes. Using five months of data collected from June 2008 to October 2008, we plot the throughput attainable to a single access point. We divide these results into bins by the aggregate number of unique APs discovered in that region during an entire month. The results are shown in Figure 4. Note that past 120 APs, there is considerably less data to form conclusions, even over a five month period.

The results show several effects. First, for smaller access point densities, the achievable throughput generally lies between 50 and 125 kB/sec; however, the large number of outliers show that in low density environments it is possible to achieve much higher throughput, but not predictably. As the density of APs grows there is generally more throughput available, as the vehicle can choose between a great number of APs and is more apt to select those with greater signal strengths. However, as the number of APs grows to as high as 120 or more, throughput is generally as good as lower numbers of APs. **Result 3: With the density of APs available in the DOME testbed, which we believe to be fairly high, we have been unable to demonstrate appreciable negative effects from interference in real-world settings.**

4.4 A Comparison of WiFi, GPRS, and 3G

Opportunistic WiFi offers the opportunity for no-cost access, but it may provide less reliable access and lower aggregate throughput. Using an experiment deployed on the buses in November 2007 with USB Prism2 WiFi and GPRS, and a second experiment in November 2008 using Mini PCI Atheros

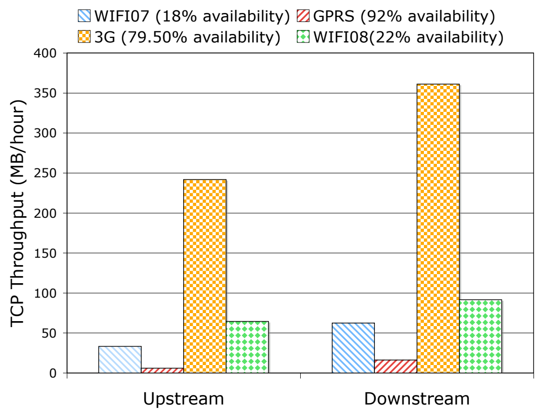

Figure 5: The throughput available from USB WiFi interfaces and GPRS during a test in 2007 and MiniPCI WiFi interfaces and 3G during a test in 2008. The legend shows the percentage of time that each interface was connected to the Internet.

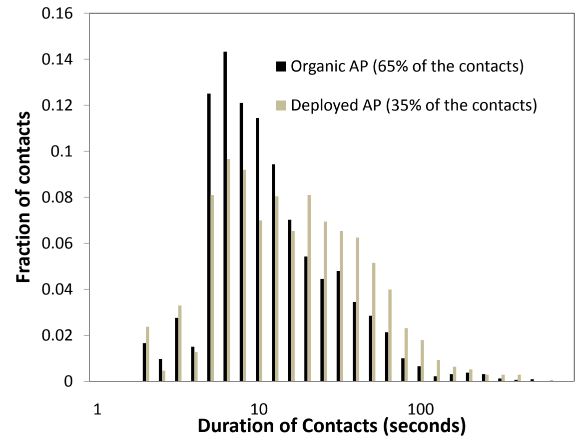

Figure 6: The duration of connections for the vehicles using the MiniPCI WiFi interfaces during a test in November 2008. The connections are separated by organic APs and managed APs (town mesh and campus wireless network).

WiFi and 3G, we compare the overall availability and upstream and downstream throughput of each of the interfaces. This experiment, shown in Figure 5, demonstrates several hardware trends.

The results show that the availability of GPRS and 3G in the DOME testbed is excellent; however, in 2007 GPRS and WiFi provided very comparable aggregate throughput over the course of a day. In 2008, the overall availability of WiFi connectivity from the vehicles had substantially improved (due to the increased range of the Atheros radios), but the overall throughput during the course of a day lags behind 3G. **Result 4: To meet the overall throughput of 3G, WiFi would need greatly expanded coverage to give connectivity nearly 90% of the time**. The amount of time needed to search and associate with APs makes this goal a challenge.

Although these results might suggest 3G as a more viable option for vehicular Internet connectivity, it should be noted that 3G networks impose a recurring cost for each device that the user carries. Consequently, it is not likely that municipalities offer free 3G access within downtown or commercial areas, nor is it likely for a university to do so on its campus. In such cases, open WiFi-based solutions still remain a relevant alternative.

4.5 Comparison of Organic and Planned WiFi

DOME incorporates three types of WiFi networks: the town-wide managed mesh network planned and deployed specifically to support DOME, with APs mounted outside and directly over the roadway; the managed campus-wide WiFi network, which is a planned deployment, but was deployed primarily for indoor access with some outdoor coverage; and the organic WiFi APs which are unmanaged and were deployed in an ad hoc manner. To examine one aspect of these deployments, we measured the durations of the WiFi connections from vehicular nodes. It is clear that a planned network should have greater connectivity durations, as managed networks are capable of seamlessly roaming between APs, but quantifying the effects of planned versus organic networks remains an open question. The results of this experiment are plotted in Figure 6, which shows the durations of connectivity using the MiniPCI Atheros WiFi interface in 2008.

The results show that most connections to open access points cover 40 seconds or less, while connections to the managed infrastructure sustain higher durations typically 100 seconds or less. However, one concern is that there is some bias in the speed of the vehicles in relation to the APs: the buses move at a slower rate of speed while in downtown area and near the campus where the planned networks were installed. We examined the effect of speed of the vehicles while connecting to those APs—see [17] for results. While the overall distribution does not change very much, we found that **Result 5: A larger portion of the organic contacts are made while the vehicle is stationary.** We believe this is due to organic APs not supporting roaming, and thus the managed nodes are more frequently used while the vehicle is moving. However, most of the contact time is spent using organic APs, marking them as a vital contributor to WiFi connectivity.

5. FUTURE WORK AND CONCLUSIONS

Large-scale and diverse testbeds like DOME are required to answer many questions facing next generation mobile systems. We provided insights into a subset of these questions from our deployments and experiments with DOME. While this paper highlights DOME's varied capabilities, we are constantly upgrading and expanding DOME to include a wider variety of hardware, geographic regions, and tracking temporal trends. The traces of the experiments run on DOME can be found at `http://traces.cs.umass.edu`. Within the next two years DOME will be remotely programmable in a generalized fashion through the GENI project, with each bus supporting experiments deployed as virtual machines.

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