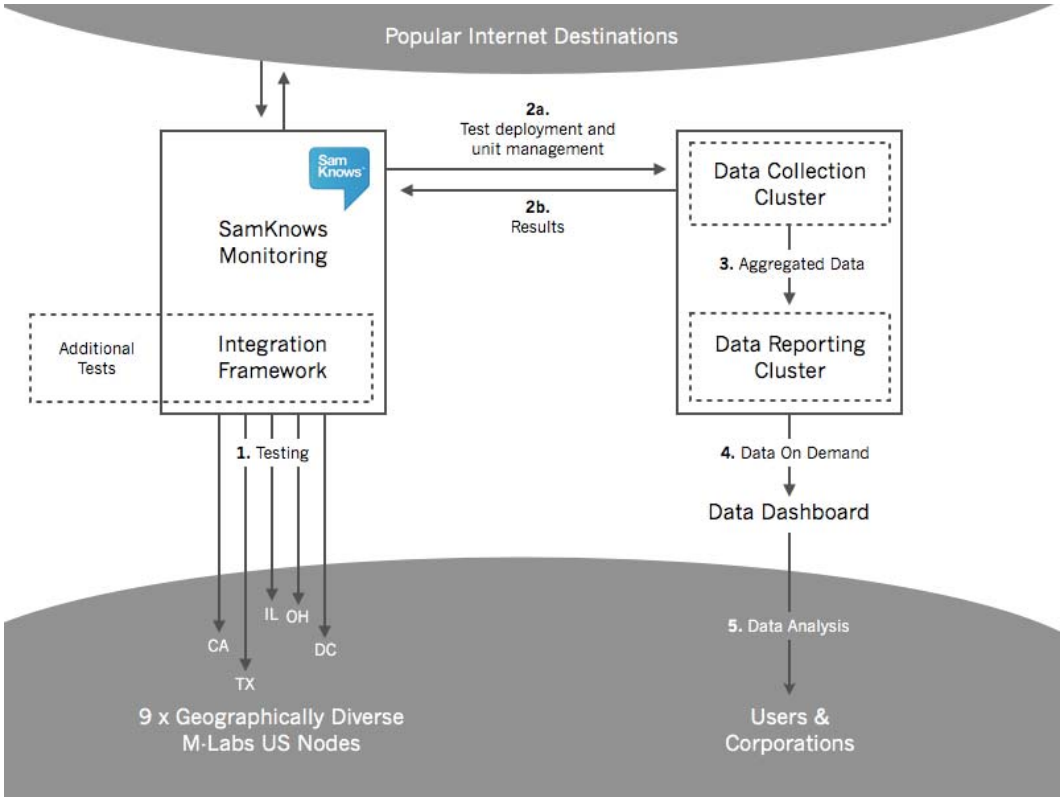
C. Testing Architecture

i. Testing Architecture Overview

As illustrated below, the performance monitoring system comprised a distributed network of Whiteboxes in the homes of members of the volunteer consumer panel, and was used to accurately measure the performance of fixed broadband connections based on real-world usage. The Whiteboxes were controlled by a cluster of servers, which hosted the test scheduler and the reporting database. The data was collated on the reporting platform and accessed via a reporting interface[19] and secure FTP site. The system also included a series of speed-test servers, which the nodes called upon according to the test schedule.

[19] Each reporting interface included a data dashboard for the consumer volunteers, which provided statistics associated with their household's broadband performance as reported by the Whitebox.



ii. Approach to Testing and Measurement

Any network monitoring system needs to be capable of monitoring and executing tests 24 hours a day, 7 days a week. Similar to the method used by the television audience measurement industry, each panelist was equipped with a Whitebox, which functioned as a router and test platform, and was self-installed by each panelist as the first consumer premise equipment connected to the provider's network after the modem. The installation of the Whitebox directly after the consumer's home Internet connection ensured that tests could be run at any time the network was connected and powered, even if all home computers were switched off.

Firmware for the Whitebox routers was developed by SamKnows with the cooperation of NETGEAR, Inc. (NETGEAR). In addition to running the latest versions of the SamKnows testing software, the routers retained all of the native functionality of the NETGEAR consumer router.

The software that came pre-installed on each of the Whiteboxes was programmed to execute a series of tests designed to measure the key performance indicators (KPIs) of a broadband connection by simulating real world usage. The tests were a suite of applications, written in the programming language C by SamKnows, which were rigorously tested by the ISPs and other stakeholders. Whiteboxes have been shown

to provide accurate information about lines with throughput rates in excess of 100 Mbps.

iii. Home Deployment

The maintenance of the existing NETGEAR firmware and all of its features was intended to allow panelists to replace their existing routers with the Whitebox. If the panelist did not have an existing router and used only a modem, they were asked to install the Whitebox as per the regular NETGEAR instructions.

This approach was the default approach used across all ISPs and service tiers. However, this approach could not easily accommodate scenarios where the panelist had a combined modem/router supplied by their ISP that had specific features that the Whitebox could not provide. Two such scenarios were:

1. Some Verizon FiOS gateways utilizing a MoCA (Multimedia over Cable) interface; and

2. AT&T U-Verse gateways providing U-Verse specific features, such as IPTV.

In such scenarios the Whitebox was connected to the existing router/gateway and all devices connected through it. In order to prevent a "double-NAT" configuration issue, in which multiple routers on the same network perform Network Address Translation (NAT) making access to the interior (SamKnows) router difficult, the Whitebox was set to dynamically switch to operate as a transparent Ethernet bridge when deployed in these scenarios. All consumer configurations were evaluated and tested by participating ISPs to confirm their suitability.

Because the Whitebox could detect all wired and wireless traffic, no tests were performed when there was any Internet activity beyond a defined threshold value. This ensured both that testing did not interfere with consumer use of their Internet service and that any such use did not interfere with or invalidate testing.

iv. Test Nodes (Off-Net and On-Net)

For the tests in this study, SamKnows employed nine core measurement or reference points that were distributed geographically across nine locations. These off-net measurement points were supplemented by additional measurement points located on the networks of some of the ISPs participating in this study. Together, the core measurement points were used to measure consumers' broadband performance between the gateway device and an available reference point that was closest in transit time to the consumer's address. The distribution of "off-net" primary reference points operated by M-Lab and "on-net" secondary reference points operated by broadband providers provided additional scientific checks and insight into broadband service performance within an ISP's network. In total, the following 147 measurement servers were deployed in conjunction with the program:

Table 4: Number of Testing Servers Overall

Server owner	#
AT&T	9
Cablevision	2
CenturyLink	14
Charter	5
Comcast	35
Cox	1
Frontier	4
Mediacom	1
MIT	1
M-Lab	48
Qwest	5
TimeWarner	13
Verizon	5
Windstream	4

OFF-NET TEST NODES

The M-Lab infrastructure served as destinations for the remote tests during this study. Nodes were located in the following major U.S. Internet peering locations:

- New York, New York (2 peering points)
- Los Angeles, and Mountain View, California
- Seattle, Washington

- Dallas, Texas
- Chicago, Illinois
- Atlanta, Georgia
- Miami, Florida

ON-NET TEST NODES

In addition to off-net nodes, some ISPs implemented their own on-net servers as an audit to the off-net nodes. Whiteboxes were instructed to test against the 'off-net' M-Lab nodes and the 'on-net' ISP nodes, when available.

The following ISPs provided on-net test nodes:

- AT&T
- Cablevision
- CenturyLink
- Charter
- Comcast
- Cox
- Frontier
- Mediacom
- Qwest
- TimeWarner Cable
- Verizon
- Windstream

The same suite of tests was scheduled for these on-net nodes as for the off-net nodes and the same server software developed by SamKnows was used regardless of whether the Whiteboxes were interacting with on-net or off-net nodes.

It is important to note that while these on-net test nodes were included in the testing, the results from these tests were used as a control set; the results presented in this study are based only on tests performed using off-net nodes. The actual results showed little difference in results obtained from on-net and off-net nodes, and the additional data from the on-net nodes provided a further confidence in test results. Results from both on-net and off-net nodes are included in the raw bulk data set. Test nodes were continually monitored for load and congestion; this end-to-end control of both the test node and Whitebox provided a high level of integrity in testing.

v. Test Node Selection

Having a geographically diverse set of test nodes would be of little use if the Whiteboxes running the test did not have a suitable mechanism to determine which node was the "best" to use. "Best" here is used to mean the node with the lowest round trip time between itself and the panelist's Whitebox.

The node actually selected might not always be the geographically closest test node to the panelist; the network route between the panelist's home and the test node will often travel via an indirect route that may take it through one or more cities. This might make another test node that is physically farther away preferable.

To identify nodes with the lowest round trip time, the Whitebox fetched a complete list of test nodes from the SamKnows infrastructure upon first execution of the test batch and performed a simple round trip time measurement to each. It then selected the test node with the lowest round trip time to test against from that point forward.

D. SamKnows Methodology[20]

Each deployed Whitebox performs the following tests:

Test	Primary measure(s)
Download speed	Throughput in Megabits per second (Mbps) utilizing three concurrent TCP connections
Upload speed	Throughput in Mbps utilizing three concurrent TCP connections
Web browsing	The total time taken to fetch a page and all of its resources from a popular website
UDP latency	Average round trip time of a series of randomly transmitted UDP packets distributed over a long timeframe
UDP packet loss	Fraction of UDP packets lost from UDP latency test
Video streaming	The initial time to buffer, the number of buffer under-runs and the total time for buffer delays[21]
Voice over IP	Upstream packet loss, downstream packet loss, upstream jitter, downstream jitter, round trip latency
DNS resolution	The time taken for the ISP's recursive DNS

[20] Specific questions on test procedures may be addressed to team@SamKnows.com.

[21] Only the total buffer delay is presented in the tabular results spreadsheet. Results of all tests are in the raw bulk data files.