QBone University and Lab Interconnect Testbed (QUALIT)

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1 Management Summary

The QUALIT grant funded two broad categories of work:

- Project-wide QBone engineering, instrumentation, and integration
- Focused workshops and measurement work relating more specifically to advanced university/DOE connectivity

Significant progress has been made in both areas and, to both, QUALIT funding has been a key enabling resource.

The QUALIT project began with the specific goal of promoting the deployment of the QBone Premium Service (an interdomain IP circuit emulation service) along key network paths between Internet2 universities and DOE labs. Although the project met with some successes in developing an implementation of the QBone Premium Service (QPS) in the Abilene backbone and engineering a QoS peering between Abilene and the DOE Science GRID, complete implementations of the QBone architecture remain elusive and partial implementations few.

Deployment of the QBone Premium Service was frustrated by a number of factors, including:

1. The need for all-or-nothing network upgrades (a participating network must be prepared to police *all* access interfaces)
2. Required diff-serv functionality in routers is either missing or comes with a crippling performance cost
3. Required operational and economic paradigm shifts for operators are too dramatic
4. Lack of clear demand (very few applications really need a virtual wire)

The QBone project has not, however, been for naught. With the support of QUALIT, the QBone project has made considerable progress in refining, testing, and clarifying the outstanding problems hindering QPS deployment. One may regard QPS as a grand experiment having with great potential, but yielding only negative results to date. As with research on tokamaks, there is an abundance of valuable data even in negative results. The economics of bandwidth and application demand may

shift one day and QPS may yet become viable. Consequently, Internet2 is suspending and carefully documenting the state of QPS, rather than simply scrapping it.

There is more value to the QUALIT project than this, however. During the course of the QUALIT grant, the specific technical focus of the QBone project shifted from building an interdomain testbed for an IP circuit emulation service (the QBone Premium Service), to building a testbed for a lightweight, incrementally-deployable form of QoS—the QBone Scavenger Service. The QBone vision has always emphasized testing QoS in an operational environment and needed to shift its focus to forms of QoS with which network engineers could begin to gain immediate experience and from which users and applications developers could begin to gain immediate value.

Despite the shift, the overall goal of the QBone project has been unwavering—to research, test, and deploy IP-layer traffic differentiation to redress congestion-related end-to-end performance problems. As was true at the project's inception, what is good for the QBone is good for advanced university/DOE connectivity. The QBone project has addressed and continues to address key UCAID, DOE, and NGI objectives. Specifically, the QBone Scavenger Service continues to gain acceptance by members of the high-energy physics community as a useful tool for allowing around-the-clock bulk data transfers that never impair the performance of interactive best-effort applications.

Looking forward, Internet2's QoS program will focus on two areas: "non-elevated" services and application QoS needs. "Non-elevated" services include those that are "lower" than best-efforts, like the QBone Scavenger Service (QBSS), as well as those that split the monolithic best-effort service class into multiple "different but equal" service classes that allow applications to trade off loss for delay. The unifying appeal of non-elevated services is that they require no policing and little operational change for providers. Moreover, they may be deployed incrementally and cheaply since they require deployment only at interfaces where congestion is a potential problem. Although these approaches offer far weaker service assurances than QPS, they deploy much more easily and have the potential to enable delay sensitive applications across congested links.

A second new area of emphasis is applications. There is an acute lack of understanding of the network performance that applications really require. Because of its very simple virtual wire service model, Premium service largely begged the issue of precisely describing application utility as a function of network performance. After all, if the application couldn't run on its own wire, then clearly there was something wrong with the application. Now that virtual wire services have been found to be undeployable, a closer scrutiny of application needs is in order. We have begun and will continue a program to study and document application QoS needs. We hope to raise awareness not only of what applications need, but also of the design tradeoffs that

exist between adding complexity to the network versus adding it to the application.

Following this management summary, this report describes in detail the evolution of the QBone project during the course of the QUALIT project (Section 2.); then, highlights the central contributions and achievements of the QUALIT project (Section 3); and finally, concludes with a breakdown of how the money was spent (Section 4).

2 Evolution of the QBone

“Quality of service” (QoS) refers to a variety of technologies that allow the network to offer differing service qualities to different users, applications, or traffic classes. The Internet2 QoS program began nearly four years ago to assure that resource-hungry advanced applications would get the network performance they need. Even at the project’s inception, it was clear that advances in optical networking would push link speeds exponentially higher and per-bit bandwidth costs lower at an equally dramatic pace. What was not clear was whether internet bandwidth would become scarce. Simultaneous with the much-heralded bandwidth explosion, Internet2 and NGI undertook an extensive set of efforts to spark explosive growth of new applications. In this light, Internet2’s QoS program may be seen as an effort to put in place a “safety belt” that could avert the success catastrophe of an inversion of bandwidth supply and demand, combined with increasing dependence on performance sensitive applications.

In May 1998, the QBone initiative was chartered to bring together a number of leading Internet2 networkers and application developers to specify an architecture for an interdomain diff-serv testbed and to facilitate its deployment through a series of workshops and exchanges of deployment experiences. Over the course of the next year, the QBone architecture was developed. The architecture specifies the requirements of a “QBone domain”, the end-to-end IP circuit-emulation service known as “QBone Premium Service” (QPS), and a set of measurement collection and reporting standards to support end-to-end debugging and auditing of QPS reservations. Additionally, the architecture specifies a common set of operational practices and procedures to be followed by network operators when requesting and responding to reservation requests and leaves a placeholder for an automated inter-bandwidth-broker signaling protocol.

By the time of the QUALIT grant application, specification of the architecture was nearly complete. The emphasis was instead on implementing the QBone architecture in Abilene and other high-performance backbones to catalyze deployment in regional, lab, and campus networks.

Despite successes, QBone deployment efforts have been frustrated by a number of factors, including a strong sense that QoS is unnecessary. Use of new resource intensive and delay sensitive applications did not grow as quickly as expected and, consequently, there has not yet been a need for a QoS safety belt. The reasons for this are complex and not fully understood. One set of factors that is fairly well understood, however, has come to be known as the “end-to-end performance problem”.

Paradoxically, most new applications can be made to run well on today’s over-

provisioned advanced networks, while at the same time, most hosts rarely achieve the network speeds they should. Applications ("advanced" or otherwise) are often hamstrung by mundane faults in the end-to-end path. Most commonly, these faults relate to poor application design, improperly configured end-system network stacks, mis-configured LANs, and faulty cabling. Rarely is network congestion the limiting factor. Both Internet2 and DOE have recognized this as a serious problem and have recently launched major end-to-end performance initiatives to address it.

Going forward, the safety belt rationale for QoS is still sound. As work on end-to-end performance progresses, an ever-increasing number of hosts will be able to achieve very high network speeds and a new high-bandwidth "killer app" may yet emerge. (Note that in relation to many commercial backbone networks Abilene is woefully underprovisioned from the perspective of host access speeds; Abilene's interior circuits could be saturated by only 25 hosts each connected to the backbone on a path no slower than 100 Mbps; moreover there are thousands, if not tens of thousands of such hosts in Internet2 today.)

Lack of bandwidth demand has not been the only factor frustrating the deployment of QPS. Support by router vendors for basic diff-serv forwarding capabilities has been surprisingly lacking. And, perhaps more fundamentally, QPS has been hamstrung by a design that requires all-or-nothing network upgrades and dramatic operational and economic paradigm shifts. The failure to spark widespread QPS deployments has had a ripple effect on the deployment of the QBone Measurement Architecture (QMA), which was designed to audit and debug QPS performance, and on QUALIT's network measurement program, which was scaled back in response. Although the world will change and QPS may yet become viable, it is increasingly a hard sell. Internet2 has decided to suspend its QPS program (at least for the time being) and to focus instead on other QoS directions.

The experience of trying to deploy a Premium service has led us to focus on "non-elevated" services. "Non-elevated" services include those that are "lower" than best-efforts, like the QBone Scavenger Service (QBSS), as well as those that split best-efforts into multiple "different but equal" service classes. Non-elevated services require no policing, admissions, billing, or other operational headaches usually associated with QoS. Moreover, they may be deployed incrementally and cheaply since they require deployment only at interfaces where congestion is a potential problem. Although these approaches offer far weaker service assurances than QPS, they deploy much more easily and have the potential to enable delay sensitive applications across congested links.

3 Contributions and Achievements

The goal of this section is to highlight the central contributions and achievements of the QUALIT project. The majority of QUALIT resources were spent on the personnel who provide technical leadership to the QBone project. This leadership has resulted in a series of highly visible collaborations between DOE and Internet2 and joint participation in the evolution of the QBone project, which has significantly raised the level of understanding of QoS and is beginning to yield deployments that tangibly benefit university-lab collaborations.

Joint Internet2 / DOE QoS Workshop

The first major collaboration was the co-sponsorship of a large and highly-successful workshop—the First Joint Internet2 / DOE QoS Workshop (February 9-10, 2000, Houston, Texas). This workshop, subtitled "Early Experiences and the Road Ahead", attracted over 150 participants including: campus network planners, advanced applications developers, chief information officers (CIOs), gigaPoP planners, and networking researchers from both the Internet2 and federal NGI communities.

A ten-member program committee chaired by John Wroclawski (MIT LCS) put together a stellar program that included twenty-two speakers, a keynote address by Yoram Bernet (Microsoft), and a concluding five-member panel. Over the course of the two-day workshop, participants took stock of the progress of the QBone initiative to date (largely architectural), characterized the challenges that faced deployers, application developers, and researchers, and looked ahead at new directions in QoS research and standards development. An online proceedings that includes abstracts, slides, and archived streaming video of the entire workshop is available at <http://qbone.internet2.edu/meetings/houston2000/> [1].

The Houston workshop was followed up by a smaller, more focused meeting at Argonne National Labs on May 26, 2000 that brought together DOE Science Grid and Internet2 QBone testbed implementers to focus on end-to-end QoS connectivity and interoperability issues effecting university-DOE application collaborations (<http://qbone.internet2.edu/qualit/agendaANLMay00.shtml>) [2]. This meeting helped to clarify the specific QoS needs of the DOE NGI applications (i.e. Corridor One, X-Ray Crystallography Collaboratory, Combustion Corridor, Earth Systems GRID, and Particle Physics Data GRID) and to identify specific action items for assuring interoperability between ESnet's DOE Science GRID testbed, the EMERGE QoS testbed, and Abilene's implementation of the QBone Premium Service.

Abilene Premium Service

Although Abilene's QBone efforts have been hamstrung by factors described elsewhere in this document, we were able to provide a policing-only service to participating connectors through the Abilene Premium Service (APS) test program [3]. Six connectors took advantage of this test program, including Argonne National Labs (ANL), where Larry Amiot and Linda Winkler collaborated with researchers at Pittsburgh Supercomputer Center (PSU), OARnet, Penn State University, and Ohio State University to test QoS services using H.323 streaming video as the driver application. APS was also used by Roch Guerin (University of Pennsylvania), his graduate students, and researchers at Northwestern University's iCAIR center to study the impact of policing and rate guarantees on streaming media applications; this work was published at SIGCOMM 2001.

The engineering and planning of the Abilene Premium Service has always been performed in close cooperation with UCAID corporate partner, Cisco Systems. Specifically, we successfully completed an early field trial (EFT) of Cisco's MPLS diff-serv aware traffic engineering functionality and presented these results to the IETF Traffic Engineering Working Group in March, 2001. We have also worked extensively with Cisco to test GSR QoS functionality and critique planned QoS capabilities with respect to their ability to implement a "virtual-wire" Premium service like QPS. UCAID's relationship with the North Carolina Internet2 Technology Evaluation Center (I-TEC) has proved invaluable to these testing activities.

Abilene / DOE Science GRID QoS Peering

A significant outcome of the Argonne connectivity meeting was the development of an engineering plan for the QoS peering of the DOE Science GRID testbed with Abilene's Premium service testbed. A dedicated Cisco 7505 QoS router (IPLS-QOS) was installed at the Abilene edge in Indianapolis and a 10 Mbps ATM PVC provisioned to the DOE Science GRID QoS router at Argonne (ANL-TB1). This peering represented the first persistent QBone peering relationship and, although the connection was barely used by DOE NGI applications researchers, it was essential to understanding a number of subtleties in Cisco's implementation of priority queuing on the 7505.

The successful engineering of the Abilene / DOE Science GRID QoS peering was highlighted at Supercomputing 2000 (SC200) in a demonstration entitled: "QoS-enabled Audio Teleportation" [4]. This demonstration used IP Premium service to provide CD-quality interactive audio under artificially induced congestion conditions along two wide-area paths. QoS-enabled audio was demonstrated between the SC200

show floor in Dallas, TX and Lawrence-Berkeley National Labs and between the SC2000 show floor and the Computer Music Center at Stanford University (CCRMA). The path to LBL traversed Abilene, the DOE Science GRID, and the LBNL QoS testbed, while the path to Stanford traversed Abilene, CalREN2, and a portion of the Stanford campus LAN. Edge routers were signalled to mark application traffic for QoS using the GARA client (<http://www-fp.mcs.anl.gov/qos/>) [5] from the Globus project. To our knowledge, this is the first demonstration of an interdomain IP Premium service. In recognition of the engineering challenges overcome for this demonstration, it was awarded the SC2000 Network Challenge award for "Best-Tuned and Most Captivating Application" (http://www-fp.mcs.anl.gov/sc2000_netchallenge/winners.htm) [6].

QBone Scavenger Service

Despite these accomplishments, broader Premium service deployment has been frustrated for reasons discussed in the previous section. Over the course of the past year, much of the effort of the QUALIT principal investigators has been directed at repositioning the QBone project and on specifying, testing, and deploying its first lightweight service—the QBone Scavenger Service (QBSS).

QBone Scavenger Service (QBSS) is an additional class of best-effort service that allows applications and leaf networks to mark their traffic voluntarily for potentially degraded treatment at downstream congestion points. QBSS is explicitly designed to meet the bulk transfer needs of demanding and sophisticated users who balance their desire for very high throughput transfers with consideration for other users who require an uncongested best-efforts experience for their interactive applications during working hours. The existence of self-policing users (who attempt to schedule their bulk transfers at periods of low network utilization) is one of the prime motivations for QBSS. QBSS allows bulk transfers to occur in the background at all hours of the day.

QBSS work has resulted in the development and testing of router configurations for Cisco GSR, 7500, 7200 and Juniper routers. These are available from the QBSS home page (<http://qbone.internet2.edu/qbss/>) [7]. Also available, are software patches for the Apache web server, the WU-FTPD FTP server, iperf (a network testing tool from NLANR) and bbcp (a file copy tool from Stanford Linear Acceleration Center) that modify these various servers to take advantage of QBSS. These patches are incorporate into master source trees for the latter two projects.

In addition to other QBSS testing and measurement work (such as TransPAC's QBSS on Juniper study [8]), SLAC has taken the lead in evaluating QBSS on Cisco's

7200 platform [9] (with positive results) and performing measurements to a variety of sites [10], including Daresbury Lab in the UK, which has funded its own QoS project [11].

Currently, interest exists in enabling QBSS on UKERNA, CERN's transatlantic link, and TransPAC. Doing so will enable bulk data transfers without deterioration of best-effort network performance. In addition, QBSS could simplify UKERNA's pricing structure from users' point of view. Currently, UKERNA charges per bit, except for bits transferred between midnight and 5am UTC. QBSS would enable the network to offer free (or cheap) service that cannot affect normal best-effort service class without the inconvenience of a fixed time window (which complicates automated bulk transfers). We are working with UKERNA to explore a QBSS pricing trial. We have also been successful in generating interest in QBSS by the European Data GRID project.

Measurement

The measurement program planned in the QUALIT proposal included a number of development and deployment activities in support of the QBone Measurement Architecture. These activities were scaled back to reflect the very limited progress of QBone Premium Service (QPS) deployments. Because of the strength of its service assurance, QPS requires stringent auditing of IP delay variation and loss at each inter-provider boundary. The QBone Scavenger Servicer (QBSS) and other non-elevated service have weaker measurement and auditing requirements. Nevertheless, good network measurement is key to understanding the performance of any network service and to finding network and host faults that degrade end-to-end performance.

Measurement activities performed under QUALIT were concentrated on the development, standardization, and deployment of active one-way delay measurement infrastructure. The first set of activities relates specifically to enhancements of the IPPM Surveyor measurement infrastructure [12], while the second set of activities relates to the creation and promotion of an Internet Engineering Task Force (IETF) open standard for the measurement of one-way network delay.

Surveyor Enhancements

The development of a CGI-based "Surveyor Summary Server" (SSS) [13] complements the raw Surveyor singleton one-way packet delay measurements by providing a convenient portal to the data. SSS serves aggregated measurement results in an HTML format convenient for on-line data-mining applications. From the SSS home page

[13], the reader may find two such examples: *Aardvark*—a Java applet that allows the user to query the SSS database and view the results graphically in cartographic and tabular formats; and *SSSpread*—an Excel spreadsheet front-end for browsing the SSS database. QUALIT funded the purchase of a high-end Dell server and RAID system to host SSS and its summary database.

Other enhancements to Surveyor focused on software developments to parameterize one-way delay measurements by diff-serv code point (DSCP). Modified software on the Surveyor nodes themselves allows one to measure and compare one-way delays for best-efforts, Premium, and Scavenger services along any measured path. This enhancement has been deployed throughout the full constellation of over seventy Surveyor measurement nodes. Surveyor also performs route monitoring along its measured paths and this too had to be parameterized by DSCP to study whether intermediate providers route traffic differently by DSCP. We enhanced Van Jacobson's *traceroute* program to mark its probe packets with specified DSCP values. Finally, other Surveyor components also required modification to support DSCP-parameterized measurements. Specifically, changes were made to the back-end raw measurement database and to various front-end visualization tools (*e.g.* <http://hartman.advanced.org/IPPMApplet/abilene/report/Report.html>).

Deployment of new Surveyor nodes under the QUALIT project was much less than anticipated. Of the four new nodes we had planned to add to the Surveyor constellation, we purchased and deployed only one (at Caltech). We expect, however, that this node will be invaluable to Harvey Newman and others on the Particle Physics Data Grid project [14], as they seek to perform precise one-way delay and packet loss measurements between Caltech, SLAC, CERN, Argonne, and other key DOE facilities.

Open One-Way Delay Measurement

We have designed and proposed in the IETF a standard protocol for the measurement of one-way delay [16]. With the increasing availability of good time sources, accurately measuring one-way delay is becoming possible for an increasingly large number of hosts. The goal of this protocol is to allow interoperable one-way delay measurements between different active measurement devices (*e.g.* Surveyors, AMPs, arbitrary workstations near good time sources). In the coming months, we plan to develop an open source software implementation and continue to advance our proposed protocol through the standards process. The hope is that one-way delay measurement generally could scale to become as commonplace as measurement of round-trip delay is today with ping.

4 Budget Commentary

Following is a discussion of the actual QUALIT budget broken down by three main expense areas: Salaries & Wages, Workshop Expenses, and Measurement Equipment. The QUALIT project enjoyed significant cost sharing by UCAID and Advanced Network & Services that we estimate to exceed \$293,000. Notable examples of cost sharing are noted below and a spreadsheet is attached for your review.

Salaries & Wages

The majority of the QUALIT budget went to salaries and wages for project personnel. Of the project's total cost of \$512,752, \$251,849 was spent on salaries and wages (inclusive of fringe benefits) and \$30,619 was spent on a subcontract to Merit Networks for Sue Hares' time. At \$100,221, the largest single personnel cost was for Stanislav Shalunov, an Internet Engineer hired specifically for the QUALIT project. Stanislav contributed significantly towards the engineering and demonstration of the Abilene / DOE Science GRID QoS peering, leadership of the QBone Scavenger Service effort, and the development of the open one-way delay measurement protocol discussed in Section 3.

Other significant personnel costs were for Ben Teitelbaum (\$56,740), Matt Zekauskas (\$7,448), and Sue Hares (as a contractor through Merit). Ben chairs the Internet2 QoS Working Group, directs UCAID's QoS program, and provided hands-on management, development, and leadership for all aspects of the QUALIT project. Matt provided leadership in the area of network measurements and managed all measurement-related personnel and projects. Sue Hares contributed to the development of the QBone Bandwidth Broker Architecture [17] and towards the planning of a bandwidth broker interoperability "bake off"¹. Overall project direction and guidance was provided by Dr. Guy Almes at no cost to the QUALIT project budget.

Work that was originally proposed for a UCAID Internet Measurement Engineer (who was never hired), was executed by four employees of Advanced Network & Services under subcontract to UCAID. Sunil Kalidindi and Min Liao implemented enhancements to the Surveyor software to parameterize one-way measurements by diff-serv codepoint. Robert Camm provided valuable support in the configuration of the Supercomputing 2000 demonstration of interdomain QoS. And finally, Bill Cervený developed and executed a number of tests of Cisco GSR QoS functionality in the North Carolina Internet2 Test and Evaluation Center (I-TEC) in support of

¹Unfortunately, Sue Hares left Merit Networks for a start-up opportunity mid-way through her planning efforts for the bake off and it did not occur.

the Abilene Premium Service test program and Supercomputing 2000 demonstration.

Finally, under contract with UCAID, Ben Chinowsky provided support for the QBone and QUALIT web sites and produced the on-line proceedings of the Joint Internet2 / DOE QoS Workshop at a cost of \$1,700.

Notable cost sharing in this area includes:

- No-cost project oversight by Guy Almes
- 50% cost sharing by Advanced Network & Services for QUALIT work performed by Ben Teitelbaum and Matt Zekauskas (\$64,189)
- QUALIT-related travel expenses for all project personnel (\$77,609)

Workshop Expenses

A second major class of expense relates to the First Joint Internet2 / DOE QoS Workshop (and follow-up connectivity meeting at Argonne). The QUALIT proposal had allocated \$12,000 towards these meetings, which was broken out into \$7,500 for Trainee/Participant Costs (travel stipends for guest speakers), \$2,000 Other Direct Costs-Materials and Supplies, and \$2,500 Other Direct Costs-Publication Costs/Document Dissemination. As successful as these meetings were, our expenses for them greatly exceeded our budget. The total expense of these workshops for UCAID (not including travel for QUALIT project personnel) was \$33,691, of which we are invoicing only \$14,240 to DOE.

Meeting expenses charged to DOE beyond those originally budgeted include: \$10,170 for a professional video crew from the University of Texas (whose high-quality footage of the workshop talks enabled quality video-on-demand to be included in the on-line workshop proceedings [1]) and \$2,200 for the rental of the conference facility.

Meeting expenses not charged to DOE (and consequently cost shared by UCAID) include \$7,533 for catered boxed lunches offered to meeting attendees and \$13,618 for a gala reception held at the Houston Museum of Natural Science².

²A corporate sponsor had been secured for the museum reception, but fell through at the last minute, leaving UCAID with the bill. Our understanding is that Department of Energy grant guidelines forbid billing any of the reception costs to DOE.

Measurement Equipment

There were two measurement equipment expenses: \$9,330 for the purchase of a high-end Dell and RAID system to host the Surveyor Summary Server and its database; and, \$6,531 for the Caltech Surveyor node. We had originally budgeted \$4,000 per Surveyor node. The Caltech node was more expensive than a typical Surveyor node because the particulars of its physical siting required the purchase of a long-reach global positioning system (GPS) antenna and an ATM OC-3 network interface card. Typical Surveyors use a cheaper 100 Mbps Ethernet network interface and a short-reach GPS antenna.

The most notable cost sharing in this area is the significant set of network externalities that benefit each new Surveyor node as it joins the constellation of over 70 Surveyor nodes. In addition, Advanced Network & Services provided significant operational support for the archival storage of QUALIT measurement data.

References

- [1] *First Joint Internet2 / DOE QoS Workshop QBone: Early Experiences and the Road Ahead*, February 9-10, 2000, Houston, Texas,
<http://qbone.internet2.edu/meetings/houston2000/>
- [2] *DOE-University QoS Connectivity Meeting*, Argonne National Labs, Friday May 26, 2000, <http://qbone.internet2.edu/qualit/agendaANLMay00.shtml>
- [3] *Abilene Premium Service Test Program* <http://www.internet2.edu/abilene/qos/>
- [4] *QoS Enabled Audio Teleportation*,
<http://apps.internet2.edu/html/qos-enabled-audio-demo.html>
- [5] *General-purpose Architecture for Reservation and Allocation (GARA)*,
<http://www-fp.mcs.anl.gov/qos/>
- [6] *SC2000 Network Challenge Winners*,
http://www-fp.mcs.anl.gov/sc2000_netchallenge/winners.htm
- [7] *QBone Scavenger Service (QBSS)*, <http://qbone.internet2.edu/qbss/>
- [8] *Juniper QBSS experiment*, <http://www.transpac.org/qbss-html/>
- [9] *SLAC QBSS Testbed*,
<http://www-iepm.slac.stanford.edu/monitoring/qbss/qbss.html>,
<http://www-iepm.slac.stanford.edu/monitoring/qbss/measure.html>
- [10] *QBSS at SLAC*, <http://www.slac.stanford.edu/grp/scs/net/case/qbss/>
- [11] *A project to investigate the effectiveness of QoS techniques*,
<http://dlitd.dl.ac.uk/public/i2qos/>
- [12] *IPPM Surveyor Project*, <http://www.advanced.org/surveyor/>
- [13] *Surveyor Summary Server (SSS)*, <http://www.advanced.org/surveyor/sss/>
- [14] *Particle Physics Data Grid*, <http://www.cacr.caltech.edu/ppdg/>
- [15] *One-way Active Measurement Protocol Requirements*,
<http://www.ietf.org/internet-drafts/draft-ietf-ippm-owdp-reqs-00.txt>
- [16] *A One-way Delay Measurement Protocol*, S. Shalunov, B. Teitelbaum, M. Zekauskas <http://www.ietf.org/internet-drafts/draft-ietf-ippm-owdp-03.txt>
- [17] *QBone Bandwidth Broker Architecture*,
<http://qbone.internet2.edu/bb/bboutline2.html>