

An Overlay Architecture for High Quality VoIP Streams

Yair Amir, Claudiu Danilov, Stuart Goose, David Hedqvist, Andreas Terzis

Abstract—The cost savings and novel features associated with Voice over IP (VoIP) are driving its adoption by service providers. Unfortunately, the Internet’s best effort service model provides no quality of service guarantees. Because low latency and jitter is the key requirement for supporting high quality interactive conversations, VoIP applications use UDP to transfer data, thereby subjecting themselves to quality degradations caused by packet loss and network failures.

In this paper we describe an architecture to improve the performance of such VoIP applications. Two protocols are used for localized packet loss recovery and rapid rerouting in the event of network failures. The protocols are deployed on the nodes of an application-level overlay network and require no changes to the underlying infrastructure. Experimental results indicate that the architecture and protocols can be combined to yield voice quality on par with the PSTN.

I. INTRODUCTION

Although subscribers are accustomed to the consistent voice quality and high reliability provided by the traditional Public Switched Telephone Network (PSTN), the promise of a single converged IP network to carry voice and data – and the cost savings therein – motivates the adoption of voice-over-IP (VoIP) technologies. However, customers expect VoIP to meet and exceed the standard of quality long offered by the Public Switched Telephone Network (PSTN). Providing IP solutions that meet the stringent requirements of high quality and reliable voice communication poses a non-trivial challenge. Delays of 100-150 msec and above are detectable by humans and can impair the interactivity of conversations. By comparison, humans are far less tolerant of audio degradation than of video degradation. Hence, to meet these requirements it is crucial to minimize primarily the network latency and secondarily packet loss as much as possible. To minimize latency, contemporary VoIP solutions use UDP as the transport protocol. However this has the potential to expose VoIP packets to packet losses and equipment failures. Although the Internet can offer reasonable quality (relatively low loss and good stability) for the majority of VoIP streams, it has been shown [2], [3], [4] that it remains vulnerable to occasional bursts of high loss and link failures that preclude it from delivering the constant, high quality service demanded for telephony.

Y. Amir, C. Danilov and A. Terzis are with the Johns Hopkins University, Department of Computer Science, Baltimore, Maryland. Email: {yairamir, claudiu, terzis}@cs.jhu.edu

S. Goose and D. Hedqvist are with Siemens Corporate Research, Inc. Princeton, New Jersey. Email: {stuart.goose, david.hedqvist}@scr.siemens.com

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This paper describes an overlay architecture that can be deployed without any changes to the underlying network infrastructure to address the problems that happen during these intervals of network loss and failures. The overlay maintains high packet delivery ratio even under high loss, while adding minimal overhead under low, or no-loss conditions. The system is based on several observations regarding VoIP applications. First, we notice that it is often possible to recover packets even within the tight delay budget of VoIP. While many VoIP streams are subject to large latencies that prohibit timely end-to-end recovery, it is possible to perform recovery for many short links that are in the order of 30 msec. Our second observation is that by dividing long end-to-end paths into multiple shorter overlay links, an overlay network architecture can localize packet recovery at the overlay hop on which the loss occurred. Thus, even for VoIP streams with end-to-end latencies considerably larger than 30 msec, the vast majority of the packet losses can be rapidly recovered on the shorter overlay hop on which they were dropped. Our third observation is that the overlays allow the deployment of a routing algorithm that maximizes packet delivery probability while conforming to VoIP delay requirements, thereby improving voice quality.

The contribution of this paper is a custom overlay network architecture targeted at VoIP by judiciously combining two complementary mechanisms: First, a real-time¹ packet recovery protocol that immediately delivers newly received packets, in a way similar to UDP, but this protocol attempts to recover missing packets. Recovery is attempted only once, and only if a packet is likely to arrive at the destination within the VoIP delay constraint. This protocol is deployed on every overlay link. Second, a routing protocol that chooses overlay paths using a synthetic metric which combines the measured latency and loss rate of each overlay link.

The architecture was implemented as part of the Spines [5] open source overlay network platform. The behavior of our protocols was evaluated under controlled network conditions on the Emulab [6] testbed and directly in the Internet on the Planetlab [7] distributed testbed. The performance of the proposed routing metric was evaluated through extensive simulations, comparing it to other metrics, on thousands of random topologies with various loss and delay link characteristics. We show that by leveraging our overlay for disseminating VoIP streams, the loss rate of the communication can be drastically reduced. For example, for a packet loss rate of 5%, our system

¹Our definition of real-time refers to timely recovery of packets on short overlay links. Protocols such as RTP, RTCP, that do not recover packets, work independently of our protocols and benefit of our higher packet delivery ratio.

can usually recover within the latency constraints all but 0.5% of the packets. This leads to a commensurate increase in the voice quality of the calls. Our results reveal that using a standard voice codec, we could achieve PSTN voice quality despite loss rates of up to 7%. Our routing metric improves overall performance by selecting paths that optimize packet delivery ratio. It outperforms routing schemes using latency, loss and hop-count as routing metrics, especially in networks with high latency in which delay constraints becomes more stringent.

When using overlay routing on general purpose computers issues such as process scheduling and application processing overhead need to be addressed. We show that when overlay routers are run with high priority, application-level routing adds a relatively small delay of under 0.15 msec, even on loaded computers where 10 processes constantly compete for CPU at the same time.

The rest of the paper is organized as follows: In Section II we present the motivation and background of our work. In Section III we introduce our overlay architecture. We present and evaluate our protocols in Section IV. The routing limitations of overlay networks and how they can be addressed in real systems are described in Section V. Section VI discusses how we can integrate our approach in the current VoIP infrastructure. Section VII presents related work, and Section VIII concludes our paper.

II. BACKGROUND

A. Voice over IP

There are several steps involved in sending voice communication over the Internet. First, the analog audio signal is encoded at a sampling frequency compatible with the human voice (8KHz in our case). The resulting data is partitioned into frames representing signal evolution over a specified time period. Each frame is then encapsulated into a packet and sent using a transport protocol (usually UDP) towards the destination. The receiver of a VoIP communication decodes the received frames and converts them back into analog audio signal.

Unlike media streaming, VoIP communication is *interactive*, i.e. participants are both speakers and listeners at the same time. In this respect, delays higher than 100-150 msec can greatly impair the interactivity of conversations, and therefore delayed packets are usually dropped by the receiver codec.

Voice quality can be adversely affected by a number of factors including latency, jitter, node or link failures, and by the variability of these parameters. The combined impact, as perceived by the end-users, is that voice quality is reduced at random. Contemporary VoIP codecs use a buffer at the receiver side to compensate for shortly delayed packets, and use forward error correction (FEC) or packet loss concealment (PLC) mechanisms to ameliorate the effect of packet loss or excessive delay. The error correction mechanisms usually add redundancy overhead to the network traffic and have limited ability to recover from bursty or sudden loss increase in the network.

In our experiments we used a well-understood, widely deployed and good quality codec, the standard ITU-T G.711 [8],

combined with its PLC mechanism [9]. The G.711 codec we used samples the audio signal at a rate of 8kHz and partitions the data stream into 20 msec frames, thus sending 160 byte packets at a rate of 50 packets/sec. VoIP quality is evaluated using an objective method described in ITU-T recommendation P.862 [10], known as Perceptual Evaluation of Speech Quality (PESQ). The PESQ score is estimated by processing both the input reference and the degraded output speech signal, similarly to the human auditory system. The PESQ score ranks speech signals on a scale from -0.5 (worst) to 4.5 (best), where 4.0 is the desired PSTN quality.

B. Internet loss characteristics

Packets are lost in the Internet due to congestion, routing anomalies and physical errors, although the percentage of physical errors is very small at the core of the network. Paxson in [3] studied the loss rate for a number of Internet paths and found that it ranged from 0.6% to 5.2%. Furthermore in that study and a follow-up [11], Paxson discovered that loss processes can be modeled as spikes where loss occurs according to a two-state process, where the states are either “packets not lost” or “packets lost”. According to the same studies, most loss spikes are very short-lived (95% are 220 msec or shorter) but outage duration spans several orders of magnitude and in some cases the duration can be modeled by a Pareto distribution. In a more recent study, Andersen et al in [4] confirmed Paxson’s earlier results but showed that the average loss rate for their measurements in 2003 was a low 0.42%. Most of the time, the 20-minute average loss rates were close to zero; over 95% of the samples had a 0% loss rate. On the other hand, during the worst one-hour period monitored, the average loss rate was over 13%. An important finding in [4] is that the conditional probability that a second packet is lost given that the first packet was lost was 72% for packets sent back-to-back and 66% for packets sent with a 10-msec delay, confirming the results in [11].

In addition to link errors and equipment failures, the other major factor contributing to packet losses in Internet is *delayed convergence* of the existing routing protocols. Labovitz et al [12] use a combination of measurements and analysis to show that inter-domain routes in the Internet may take tens of minutes to reach a consistent view of the network topology after a fault. They found that during this period of delayed convergence, end-to-end communication is adversely affected. In [13], Labovitz et al. find that 10% of all considered routes were available less than 95% of the time and that less than 35% of all routes were available more than 99.99% of the time. In a follow-up study [14], Chandra et al showed that 5% of all failures last more than 2 hours and that failure durations are heavy-tailed and can last as long as 20 hours before being repaired. In a related study performed in 2003, Andersen et al [4] showed that while some paths are responsible for a large number of failures, the majority of the observed Internet paths had some level of instability. In a different analysis [15], Boutermans et al study the effect of link failures on VoIP performance and show that a single network failure between two nodes located at San Francisco (CA) and Reston (VA)

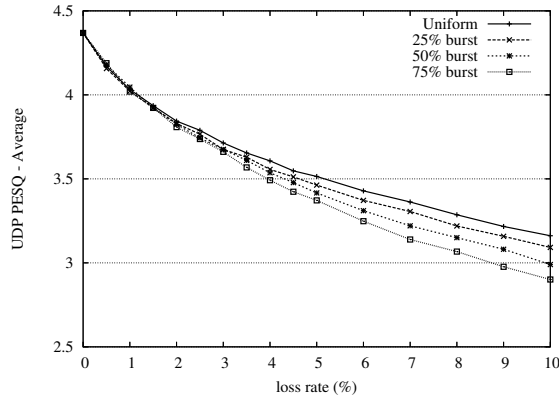


Fig. 1. Network loss - Average PESQ

affected network traffic for 50 minutes with several periods of down-time, of which one lasted 12 minutes. All these statistics indicate the Internet today is not ready to support high quality voice service as we are going to show in the following section.

C. Voice quality degradation with loss

We evaluated the effect of losses that mimic realistic Internet patterns on VoIP quality. Our evaluation is based on the standardized PESQ measure. To do so, we instantiated a network with various levels of loss and burstiness (we define burstiness as the conditional probability of losing a packet when the previous packet was lost) in the Emulab [6] testbed, and measured the quality degradation when sending a VoIP stream on that network.

Emulab is a testing environment that allows deployment of networks with given characteristics composed of real computers running Linux, connected through real routers and switches. Link latency, capacity and loss² are emulated using additional computers that delay packets or drop them with certain probability or if their rate exceeds the requested link capacity. All the Emulab machines are also directly connected through a local area network through which they are managed and can be accessed from the Internet. On this local area network we constantly monitored the clock synchronization between the computers involved in our experiments and accurately adjusted our one-way latency measurements.

We used the G.711 codec with PLC to transfer a 5 minute audio file using UDP over the lossy network, repeating each experiment for 20 times. The network had a 50 msec delay and 10 Mbps capacity, enough to emulate a trans-continental long-distance call over a wide area network. We finally decoded the audio file at the destination, divided it into 12 second intervals corresponding to normal conversation sentences, and compared each sentence interval with the original to generate its PESQ score.

Figure 1 shows the average PESQ score of all the sentence intervals as a function of loss rate and burstiness of the link. We can see that on average, the G.711 codec can handle up to

²Emulab cannot set conditional loss probability on the links. For burstiness experiments we dropped packets with conditional probability at the application level, before processing them.

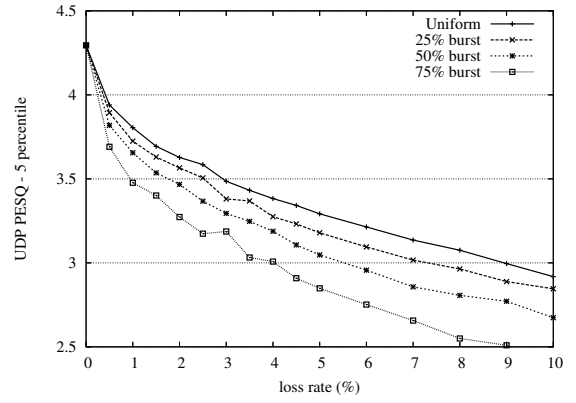


Fig. 2. Network loss - 5 percentile PESQ

1% loss rate, while keeping a PESQ score higher than 4.0 (the expected PSTN quality level). Burstiness does not play a major role until the loss rate is relatively high, when the voice quality is anyway low. However, given the regular expectancy of high quality phone calls, we also need to analyze the most adversely affected voice streams. Figure 2 presents the 5 percentile of the above measurements. We can see that for the most affected streams burstiness does have a significant impact, and even at 0.5% loss rate the G.711 codec cannot provide PSTN standard voice quality. At 0.5% loss and 75% burstiness the PESQ score dropped to 3.69.

Considering the fact that current loss rate measurements in the Internet average at about 0.42% with an average burstiness of 72%, and that occasionally loss can be even much higher, these experiments show that new solutions are required to improve the quality of VoIP traffic if it is to compete with the existing PSTN.

III. AN OVERLAY ARCHITECTURE

Overlay networks allow easy deployment of new services, as they allow full control over the protocols running between participating nodes. While the Internet provides generic communication solutions, an overlay network usually has limited scope and therefore can deploy application aware protocols that would otherwise be impractical to deploy directly in the larger Internet. Most overlay networks, including ours, run above the networking infrastructure, and therefore do not require any change in the network routers or IP protocols.

The use of overlay networks usually comes with a price, partially due to the management overhead of the overlay, but mostly due to the sub-optimal placement of the overlay routers in the physical network topology. However, overlays are small compared to the global underlying network, and therefore protocols that exploit the relatively limited size and scope of overlays not only can overcome these drawbacks, but can actually offer better performance to end-user applications.

The overlay handles traffic for multiple connections in various directions, such that every connection can have a limited number of intermediate overlay hops. Previous work [16] [17] shows that increasing the number of nodes in an overlay follows a diminishing return function. At some early point,

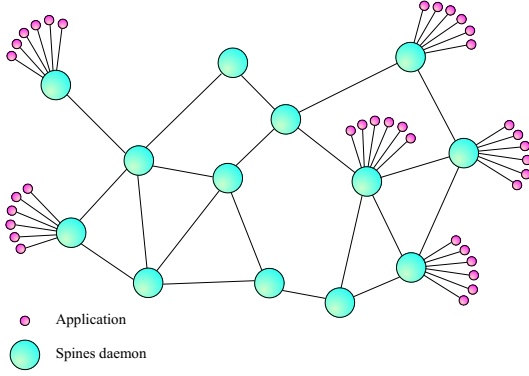


Fig. 3. A Spines overlay

the benefit of adding additional nodes to an existing overlay is small, and is overcome by the overhead associated with a larger overlay. Therefore we opt for having a relatively small overlay (tens to hundreds of nodes) with direct link latencies in the order of milliseconds or tens of milliseconds.

A. Spines

Spines [5] is an open source overlay network that allows easy deployment and testing of overlay protocols. It runs in user space, does not need special privileges or kernel modifications, and encapsulates packets on top of UDP. Spines offers a two-level hierarchy in which applications (clients) connect to the closest overlay node, and this node is responsible for forwarding and delivering data to the final destination through the overlay network. The benefit of this hierarchy is that it limits the size of the overlay network, thus reducing the amount of control traffic exchanged. An example of a Spines overlay network is shown in Figure 3. Overlay nodes act both as servers (accepting connections from various applications) and as routers (forwarding packets towards clients connected to other overlay nodes). Applications may reside either locally with the Spines nodes or on machines different than the overlay node they connect to. In this paper we focus only on the overlay protocols and in all of our experiments, applications reside either on the same machine as their overlay node, or on a different machine connected through a local area network to the overlay node. We expect that the overlay nodes are connected through high latency wide area links.

In order to connect to a Spines overlay node, applications use a library that enables UDP and TCP communication between the application and the selected Spines node. The API offered by the Spines library closely resembles the Unix socket interface, and therefore it is easy to port any application to use Spines. We describe in Section VI the necessary steps to adapt current VoIP applications to use Spines. Each application is uniquely identified by the IP address of the overlay node it connects to, and by an ID given at that node, which we call *Virtual Port*. Spines provides both reliable and best-effort communication between end applications, using the applications' node IP address and the *Virtual Port* in a way similar to TCP and UDP. Similar to the `socket()` call, a `spines_socket()` function returns a descriptor that can be used for sending and receiving

data. A `spines_sendto()` call resembles the regular `sendto()`, and a `spines_recvfrom()` resembles the regular `recvfrom()`, with similar parameters. *Virtual Ports* are only defined in the context of an overlay node, and have no relation to the actual operating system ports.

Spines nodes connect to each other using *virtual links* forming the overlay network. Spines offers a number of protocols on each virtual link, including a best effort service, a TCP-fair reliable protocol [16] and a real time recovery protocol [1].

Each overlay node pings its direct neighbors periodically to check the link status and latency. Round trip time measurements are smoothed by computing an exponential weighting average. Spines nodes add a link specific sequence number on every data packet sent between two neighboring overlay nodes. The receiving overlay node uses this sequence number to estimate the loss rate of overlay links. Upon receiving a number of packets out of order (in our implementation, three), the node decides that a loss event happened. The loss rate is computed by averaging the number of packets received between two subsequent loss events over the last L loss events (in our implementation $L = 50$). This way, the loss estimate converges relatively fast when loss rate increases (fewer packets will be received between two loss events), but is conservative in switching to temporarily low-loss overlay links. Based on link loss and latency, a cost for each link is computed as described in Section IV-B and propagated through the overlay network by an incremental link-state protocol that uses reliable flooding mechanism.

The control traffic required for maintaining the overlay network is small compared to the overall data traffic, consisting in our implementation of periodical *hello* messages and *link updates*. One 32 byte hello message is sent every second by each of the two end-nodes of a direct link. A single link update is propagated to all the nodes in the overlay through a reliable flooding algorithm only in case of a network change, such as a variation in the estimation of delay or loss rate of the link, or when a link or node goes down. On the initial state transfer the entire routing table is transferred. In this case, as well as when multiple network events happen simultaneously, multiple link updates are aggregated, so that a regular Ethernet packet can carry between 60 and 90 distinct updates, depending on the sparsity of the network. In the current implementation, Spines scales to up to several hundred overlay nodes, and up to a thousand clients per node. Spines detects network failures through its hello protocol in under 10 seconds. Our experiments on the Planetlab network show that reducing the failure detection interval to less than 10 seconds increases the chance of route instability.

IV. PROTOCOLS FOR INCREASING VOIP QUALITY

Traditional VoIP systems use UDP to transfer data, exposing the audio channels to packet loss. One of the main reasons for not using end-to-end retransmissions is that lost packets, even when recovered end-to-end from the source, are not likely to arrive in time for the receiver to play them. Overlay networks break end-to-end streams into several hops, and even though an overlay path may be longer than the direct Internet

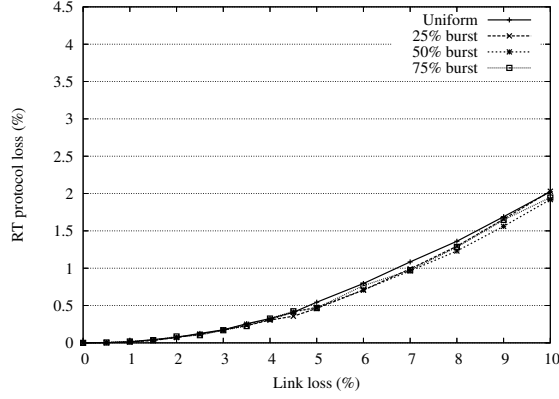


Fig. 4. Real-time recovery loss - 1 link

path between the two end-nodes, each individual overlay hop usually has smaller latency, thus allowing localized recovery on lossy overlay links.

A. Real-time recovery protocol

Our overlay links run a real-time protocol that recovers packets only if there is a chance to deliver them in time, and forward packets even out of order to the next hop. We describe our real time recovery protocol next:

- Each overlay node keeps a circular packet buffer per outgoing link, maintaining packets sent within a time equal to the maximum delay supported by the audio codec. Packets are dropped out of the buffer when they expire, or when the circular buffer is full. In our implementation, the circular buffer can maintain 1000 VoIP packets, totaling 160 KBytes.
- Intermediate nodes forward packets as they are received, even out of order.
- Upon detecting a loss on one of its overlay links, a node asks the upstream node for the missed packets. A retransmission request for a packet is only sent once. We only use negative acknowledgments, thus limiting the amount of traffic when no packets are lost.
- When an overlay node receives a retransmission request it checks in its circular buffer, and if it has the packet it resends it, otherwise it does nothing. A token bucket mechanism regulates the maximum ratio between the number of retransmissions and the number of original packets sent. This way we limit the number of retransmissions on lossy links.
- If a node receives the same packet twice (say because it was requested as a loss, but then both the original and the retransmission arrive), only the first instance of the packet will be forwarded towards the destination.

The protocol does not involve timeouts and never blocks for recovery of a packet. On the other hand, this is not a fully reliable protocol and some of the packets will be lost in case the first retransmission attempt fails. Such events can appear when a packet is lost, the next packet arrives and triggers a retransmission request, but the retransmission request is also lost. For a link with independent loss rate p in both directions,

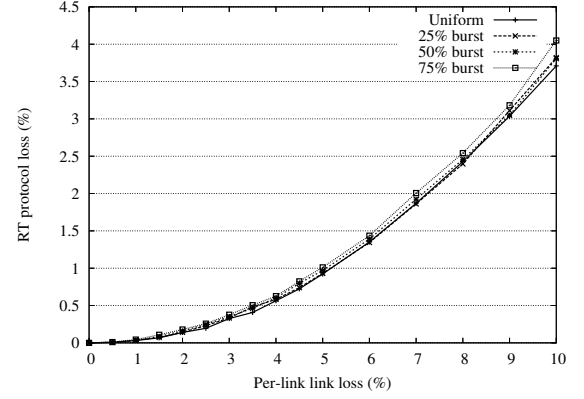


Fig. 5. Real-time loss recovery - 2 concatenated links

the above sequence of events will happen with probability $p \cdot (1 - p) \cdot p = p^2 - p^3$. Another significant case is when the retransmission request does arrive, but the retransmission itself is lost, which can happen with probability $p \cdot (1 - p) \cdot (1 - p) \cdot p = p^2 - 2p^3 + p^4$. Other types of events, that involve multiple data packets lost can happen, but their probability of occurrence is negligible. We approximate the loss rate of our real-time protocol by $2p^2 - 3p^3$, assuming that the loss probability on the link is uniform³.

The delay distribution of packets follows a step curve, such that for a link with one way delay T and loss rate p , $(1 - p)$ fraction of packets arrive in time T , $(p - 2p^2 + 3p^3)$ are retransmitted and arrive in time $3T + \Delta$, where Δ is the time it takes the receiver to detect a loss, and $(2p^2 - 3p^3)$ of the packets will be lost by the real time recovery protocol. For a path that includes multiple links, the delay of the packets will have a composed distribution given by the combination of delay distributions of each link of the path. The time Δ it takes the receiver to trigger a retransmission request depends on the inter-arrival time of the packets (the receiver needs to receive a packet to know that it lost the previous one) and on the number of out of order packets that the protocol can tolerate. For a single VoIP stream, packets usually carry 20 msec of audio, so they arrive at relatively large intervals. In our overlay approach, we aggregate multiple voice streams within a single real-time connection on each link. The overlay link protocol handles packets much more often than a single VoIP stream, and therefore the inter-arrival time of the packets is much smaller. Standard TCP protocol needs three packets out of order before triggering a loss. Since latency is crucial for VoIP applications, and as packet reordering is a rare event [18], in our experiments we trigger a retransmission request after receiving the first out of order packet.

We implemented the real time protocol in the Spines overlay network platform and evaluated its behavior by running Spines on Emulab. Figure 4 shows the loss rate of the real time recovery protocol on a 10 msec link with various levels of loss and burstiness, and Figure 5 shows the combined loss for two concatenated 10 msec links that experience the same amount

³In many cases, the loss rate probability may not be uniform. Later in the paper, we investigate the impact of burstiness on our protocols.

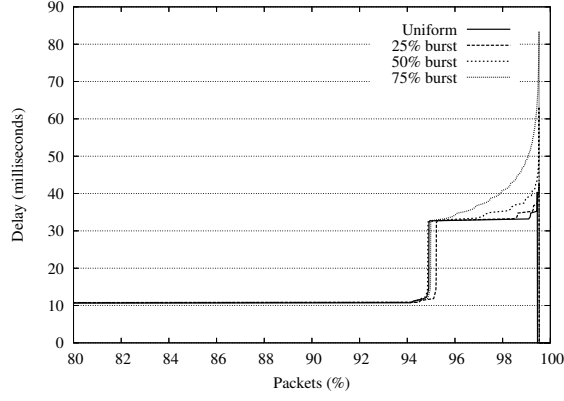


Fig. 6. Delay distribution - 1 link, 5% loss

of loss and burstiness, in both directions, running Spines with the real-time protocol on each link. For each experiment, we generate traffic representing the equivalent of 10 VoIP streams for a total of two million packets of 160 bytes each, and then average loss rate was computed. We can see that the level of burstiness on the link does not affect the loss rate of the real-time protocol. The real-time loss rate follows a quadratic curve that matches our $2p^2 - 3p^3$ estimate. For example, for a single link with 5% loss rate, applying the real-time protocol reduces the loss rate by a factor of 10, to about 0.5% regardless of burstiness, which yields an acceptable PESQ score (see Figure 1).

For the single 10 msec link experiment with 5% loss rate, the packet delay distribution is presented in Figure 6. As expected, 95% of the packets arrive at the destination in about 10 milliseconds. Most of the losses are recovered, showing a total latency of 30 msec plus an additional delay due to the inter-arrival time of the packets required for the receiver to detect the loss, and about 0.5% of the packets could not be recovered. Lost packets are shown as no delay measured, between 99.5 and 100%.

In the case of uniform loss probability the delay of the recovered packets is almost constant. However, when the link experiences loss bursts, multiple packets are likely to be lost in a row, and therefore it takes longer for the receiver to detect the loss. The increase of the interval Δ (the time it takes to detect a loss) results in a higher delay for the recovered packets. Obviously, the higher the burstiness, the higher the chance for consecutive losses, and we can see that the packet delay is mostly affected at 75% burstiness.

Figure 7 shows the delay distribution for the two-link network, where both links experience 5% uniform distribution loss rate. As in the single link experiment, most of the losses are recovered, with the exception of 1% of the packets. We notice, however, a small fraction of packets (slightly less than 0.25%) that are lost and recovered on both links, and that arrive with a latency of about 66 msec. This was expected to happen with the compound probability of loss on each link, $p_c = 0.05 \cdot 0.05$. Burstiness results for the two-link network, not plotted in the figure, follow the same pattern as shown in Figure 6.

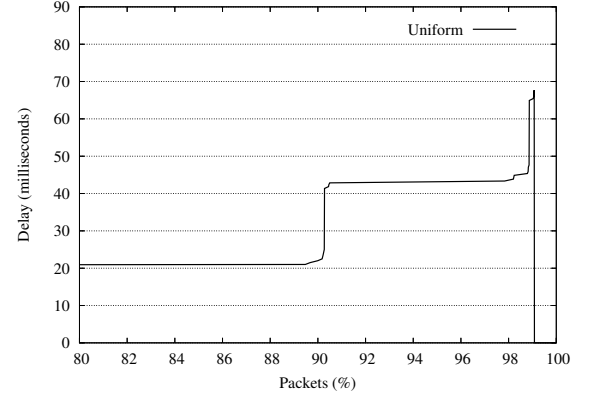


Fig. 7. Delay distribution - 2 concatenated links, 5% loss each

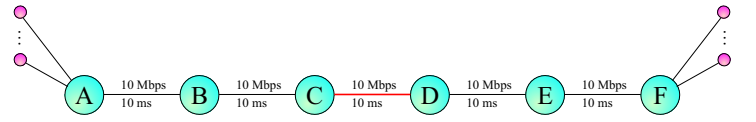


Fig. 8. Spines network - 5 links

In order to evaluate the effect of local recovery on voice quality we ran the same experiment depicted in Figure 1 and Figure 2 on top of a Spines overlay network. We divided the 50 msec network into 5 concatenated 10 msec links as shown in Figure 8, ran Spines with the real-time protocol on each link, and sent 10 VoIP streams in parallel from node A to node F. We generated losses with different levels of burstiness on the middle link C – D and set the network latency threshold for the G.711 codec to be 100 msec.

Figure 9 presents the average PESQ score of all the sentence segments in the G.711 streams using Spines, and compares it with the results obtained when sending over UDP directly. Since most of the packets are received in time to be decoded at the receiver, we can see that when using Spines, regardless of burstiness, the G.711 codec can sustain on average even network losses of 7-8% with PSTN voice quality.

As discussed earlier, users of telephony services expect high quality service. Therefore, in addition to average performance characteristic, it is important to look at the performance of the worst cases. Figure 10 shows the quality of the worst 5 percentile sentence intervals. We can see that the codec can handle up to 3.5% losses with PSTN quality and even for the worst 5% sentence segments, the burstiness did not play a major role in the voice quality.

B. Real time routing for audio

The real time protocol recovers most of the missed packets in case of occasional, or even sustained periods of high loss, but if the problem persists, we would like to adjust the overlay routing to avoid problematic network paths.

Given the packet delay distribution and the loss rate of the soft real-time protocol on each overlay link, the problem is how to find the overlay path between a pair of source and

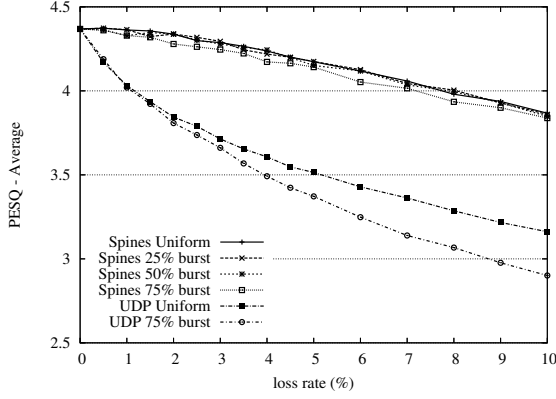


Fig. 9. Real-Time protocol - Average PESQ

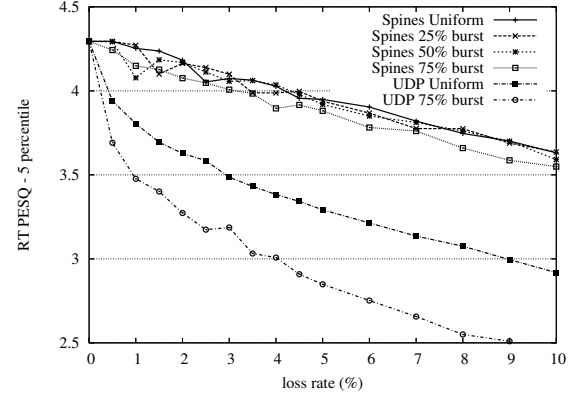


Fig. 10. Real-Time protocol - 5 percentile PESQ

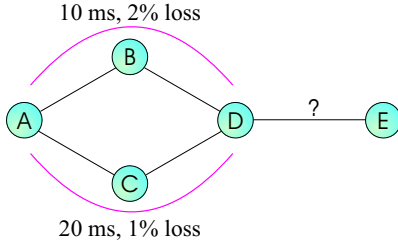


Fig. 11. Two-metric routing decision

destination, for which the packet delay distribution maximizes the number of packets that arrive within a certain delay, so that the audio codec can play them. The problem is not trivial, and deals with a two metric routing optimizer. For example, in Figure 11, assuming a maximum delay threshold for the audio codec to be 100 msec, if we try to find the best path from node A to node E, even in the simple case where we do not recover packets, we cannot determine which partial path from node A to node D is better (maximizes the number of packets arriving at E within 100 msec) without knowing the latency of the link D-E. On the other hand, computing all the possible paths with their delay distribution and choosing the best one is prohibitively expensive as the network size increases.

However, if we can approximate the cost of each link by a metric dependent on the link's latency and loss rate, taking into account the characteristics of our real-time protocol and the requirements of VoIP, we can use this metric in a regular shortest path algorithm with reasonable performance results. Our approach is to consider that packets lost on a link actually arrive, but with a delay T_{max} bigger than the threshold of the audio codec, so that they will be discarded at the receiver. Then, the packet delay distribution of a link will be a three step curve defined by the percentage of packets that are not lost (arriving in time T), the percentage of packets that are lost and recovered (arriving in $3T + \Delta$), and the percentage of packets missed by the real-time protocol (considered to arrive after T_{max}). The area below the distribution curve represents the expected delay of the packets on that link, given by the formula: $T_{exp} = (1-p) \cdot T + (p-2p^2+3p^3) \cdot (3T+\Delta) + (2p^2-3p^3) \cdot T_{max}$. Since latency is additive, for a path consisting of

several links, our approximation for the total expected delay will then be the sum of the expected delay of each individual link. We call this metric *expected latency cost function*.

We evaluated the performance of the *expected latency* based routing and compared it with several other cost metrics described below. We used the BRITE [19] topology generator to create random topologies using the Waxman model, where the probability to create a link depends on the distance between the nodes. We chose this model because it generates mostly short links that fit our goal for localized recovery. We assigned random uniform loss from 0% to 5% on half of the links of each topology, selected randomly. Since routing decisions are done at relatively large intervals (10 seconds or more), the short term burstiness of the losses does not influence our cost metric, and therefore we only looked at the long term loss average in this experiment. We considered every node generated by BRITE to be an overlay node, and every link to be an overlay edge. For each topology we determined the nodes defining the diameter of the network (the two nodes for which the shortest latency path is longest), and determined the routing path between them given by different cost metrics.

By adjusting the size of the plane in which BRITE generates topologies, networks with different diameters are created. For each network diameter we generated 1000 different topologies and evaluated the packet delivery ratio between the network diameter nodes when running the real-time protocol on the links of the network, using different routing metrics. Note that while we adjusted the size of the network plane, the placement of the nodes and individual link latencies was chosen randomly by BRITE. Figure 12 shows the average delivery ratio for network topologies with 15 nodes and 30 links, and Figure 13 shows the delivery ratio for network topologies with 100 nodes and 200 links. For a link with direct latency T and loss rate p , considering an audio codec threshold $T_{max} = 100$ msec and the packet inter-arrival time $\Delta = 2$ msec, the cost metrics used are computed as follows:

- Expected latency: $Cost = (1-p) \cdot T + (p-2p^2+3p^3) \cdot (3T + \Delta) + (2p^2-3p^3) \cdot T_{max}$
- Hop distance: $Cost = 1$
- Link latency: $Cost = T$
- Loss rate: $Cost = -\log(1-p)$
- Greedy optimizer: We used a modified Dijkstra algorithm

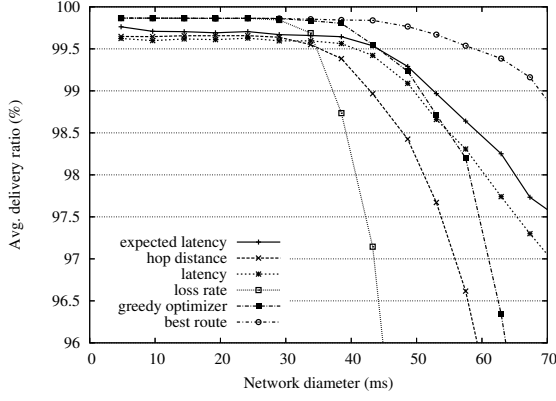


Fig. 12. Comparing routing metrics - 15 node networks

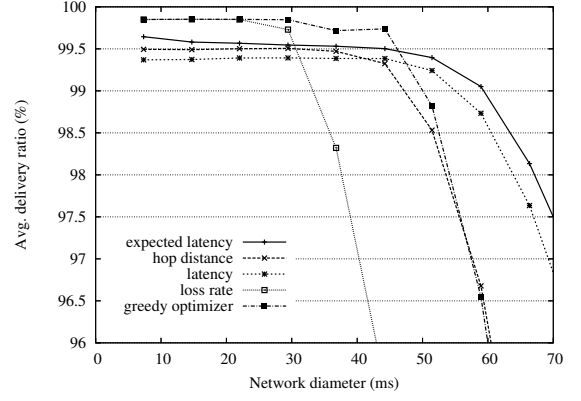


Fig. 13. Comparing routing metrics - 100 node networks

that, at each iteration, computes the delay distribution of the selected partial paths and chooses the one with the maximum delivery ratio.

- **Best route:** All the possible paths and their delay distributions were computed, and out of these the best one was selected. Obviously, this operation is very expensive, mainly because of the memory limitation of storing all combinations of delay distributions. Using a computer with 2GB memory we could not compute the best route for networks with more than 16 nodes.

As expected, for small diameter networks the loss-based routing achieves very good results, as the delay of the links is less relevant. With the increase in the network diameter, the latency-based routing achieves better results. At high latencies, the packet recovery becomes less important than the risk of choosing a highly delayed path, with latency more than the codec threshold. The expected latency routing achieves lower delivery ratio than the loss-based routing for small diameter networks, but behaves consistently better than the latency-based routing. The slight drop in delivery ratio for low diameter networks is causing just a small change in VoIP quality (see Figures 1 and 2), while the robustness at high network delays is very important. Interestingly, the greedy optimizer fails at high latency networks, mainly due to wrong routing decisions taken early in the incremental algorithm, without considering the full topology.

This experiment shows that the *expected latency* metric, while being comparable with other routing metrics for small diameter networks achieves better routing in high latency networks, exactly where we need it the most.

While an efficient link cost metric is essential for finding routes that provide high quality VoIP, it is important to trigger fast routing decisions that avoid links that suddenly fail, or experience high levels of congestion. Internet studies mentioned in Section II show that it can take up to minutes, or tens of minutes until the Internet routing converges in case of a failed link. Since overlay networks are smaller compared to the Internet, they can afford closer monitoring of the networking resources and faster decisions in case the network conditions change, in the order of seconds or tens of seconds. The dynamic of the routing decisions is a trade-off between how fast the system can detect link failures or

network congestion, and the likelihood of routing instability and oscillations. In our experiments on Planetlab we noticed that allowing consecutive route changes due to a single link to happen faster than 10 seconds apart, can create occasional instability that leads to VoIP quality degradation. Therefore, in the current implementation, Spines considers a link to be down if two neighboring nodes cannot communicate through it for more than 10 seconds. Moreover, for links that are available but change their network characteristics (latency, loss rate), Spines requires at least 30 seconds between two consecutive cost updates of the same link.

V. DEPLOYMENT CONSIDERATIONS FOR OVERLAY NETWORKS

Running overlay node software in user level gives us great flexibility and usability, but comes at the expense of packet processing through the entire networking stack, and process scheduling on the machines running the overlay nodes.

Executing overlay network functionality on loaded computers naturally degrades the performance of the overlay system. This degradation is critical especially for latency sensitive VoIP streams. For example, if the overlay daemon runs as a user level process on a computer that has other CPU intensive processes, it is common for the overlay network system not to be scheduled for several hundred milliseconds, and even seconds, which of course, is not useful for VoIP. In fact, our experience with another messaging system, the Spread toolkit [20] that is commonly deployed on large websites, shows that on heavily loaded web servers a process may be scheduled only after eight seconds. It is common practice on such systems to assign the messaging system higher priority (real time priority in Linux). Note that messaging systems consume negligible amounts of processing when they do not need to send or receive packets. Therefore, increasing their priority does not affect performance of other applications unless packets - that they probably need, anyway - are sent or received. For a VoIP service it is reasonable to expect that the overlay nodes will be well provisioned in terms of CPU and networking capabilities.

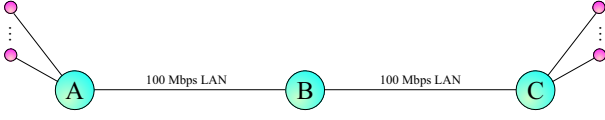


Fig. 14. Spines network - 2 links

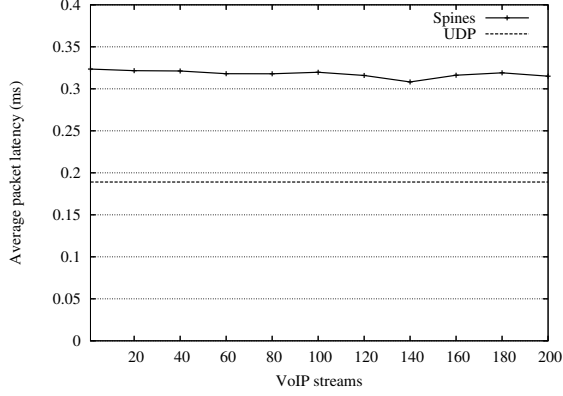


Fig. 15. Spines forwarding delay

A. Routing performance in Spines

It is interesting to evaluate the overhead of running the overlay nodes as regular applications in the user space, and how the routing performance is affected by the amount of traffic or load on the computers. We deployed Spines in Emulab on a three node network as shown in Figure 14, where the middle node *B* had two network interfaces and was directly connected to nodes *A* and *C* through local area links. All the computers used were Intel Pentium III 850MHz machines. The one-way latency between node *A* and node *C* measured sending 160 byte packets and adjusted with the clock difference between the nodes was 0.189 msec.

We ran a Spines instance on each node, using the real-time protocol on the links *A – B* and *B – C*. Then we sent a varying number of voice streams in parallel (from 1 to 200 streams), consisting of 20000 packets of 160 bytes each, from node *A* to node *C* using Spines. We measured the one way latency of each packet, adjusted by the clock difference between machines *A* and *C*. When forwarding 200 streams, the middle node *B* running Spines showed an average CPU load of about 40%. However, the sending node *A*, on which both Spines and our sending application were running, reached a maximum 100% CPU utilization.

Figure 15 shows the average latency of packets forwarded through Spines as the number of parallel streams increases from 1 to 200, and compares it to the base network latency measured with UDP probes. The standard deviation of all the measurements was a very low 0.012, and the highest single packet latency measured, which happened when we sent 200 streams in parallel, was 0.963 msec. What we see is that regardless of the number of streams, the three Spines nodes add a very small delay totaling about 0.15 msec due to user-level processing and overlay routing.

We evaluated the routing performance of Spines on a CPU

loaded computer by running a simple *while(1)* infinite loop program on the middle node *B*, and repeated the above experiment. Running Spines with the same priority as the loop program, when forwarding a single voice stream we achieved a very high packet delay average of 74.815 msec, and the maximum packet delay was 154.468 msec. When competing with 4 loop programs in parallel, with the same priority as Spines, the average packet delay for a single stream went up even more to 298.354 msec (about 900 times more than without CPU competing applications), and the maximum packet delay was 604.917 msec. Obviously, such delays are not suitable for VoIP. However, when we set real-time priority for the Spines process, the high CPU load did not influence our performance. Even when competing with 10 loop programs and a load of 200 streams, the average packet delay was a low 0.315 msec and the maximum packet delay measured was 0.469 msec.

Our conclusion is that the performance of overlay routing at the application level can be highly affected by the load on the supporting computers. However, this overhead can be easily reduced to negligible amounts compared to wide area latencies simply by increasing the priority of the overlay node applications. This should not be a problem in general, as the overlay node applications do not use CPU unless they send packets, and if they do need to send packets, in a system dependent on real-time packet arrival, the overlay nodes should not be delayed.

B. Case study: Planetlab

Planetlab [7] is a large distributed testbed of computers connected through the public Internet. Currently Planetlab has 583 nodes at 275 sites. Unlike Emulab, which has a reservation mechanism that completely allocates computers to a particular experiment, Planetlab is a shared environment. Experiments run within *slices* created on several (or all) Planetlab computers. Each slice acts as a virtual machine on each computer and shares the resources with other users' slices. In the current incarnation of Planetlab it is not possible to set real-time process priorities, and the available CPU time depends on the applications that run at the same time. Due to the high CPU load on the machines, Planetlab losses happen mostly at the overlay nodes, happen in large bursts (tens to hundreds of packets lost in a row), and are mainly caused by delays in scheduling the receiver application while competing with other processes (note that due to the stringent delay requirements of VoIP applications, packets that arrive *late* are discarded and are therefore equivalent to lost packets). As such, we believe that Planetlab, in its current configuration, is not suitable for deploying VoIP applications.

However, it is useful to evaluate the behavior of our overlay protocols on an Internet testbed with realistic latency characteristics. In a first experiment we deployed Spines on 32 Planetlab nodes that we found to be synchronized to under 20 msec, and that were located at 26 sites, shown in Table I, within the North American continent. The maximum delay between any two sites was 47 msec, and appeared between MIT and Internet2 - Denver. Note that our overlay protocols

TABLE I
PLANETLAB SITES - CONTINENTAL US

Canarie - Calgary	Canarie - Halifax
Canarie - Toronto	Harvard University
Internet2 - Atlanta	Internet2 - Chicago
Internet2 - Denver	Internet2 - Indianapolis
Internet2 - Washington	Johns Hopkins Information Security Institute
Massachusetts Institute of Technology	New York University
Northeastern University CCIS	Princeton
Purdue	Rutgers University
University of Florida - ACIS Lab	University of Georgia
University of Illinois at Urbana-Champaign	University of Kansas
University of Maryland	University of Pennsylvania
University of Rochester	University of Wisconsin
Washington University in St Louis	Wayne State University

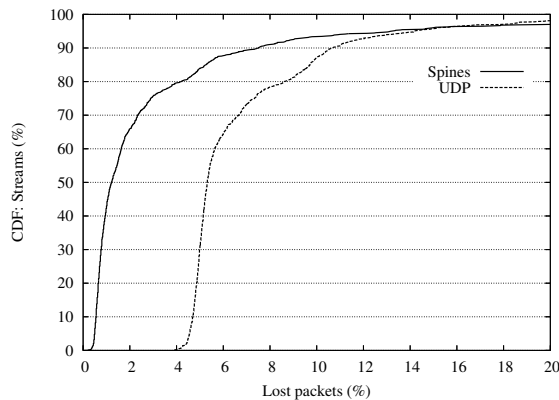


Fig. 16. Planetlab US - percentage of streams that *lost* at least a certain percentage of packets

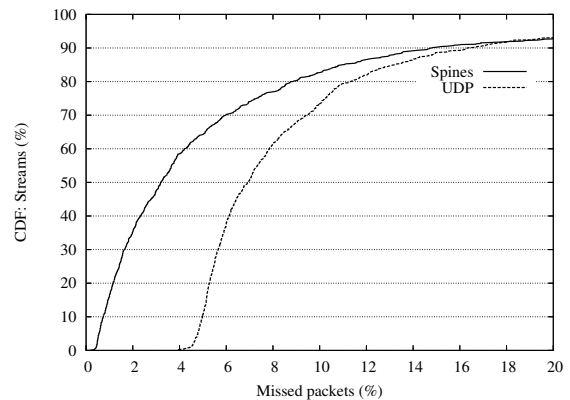


Fig. 17. Planetlab US - percentage of streams that *missed* at least a certain percentage of packets

do not require clock synchronization, however we do need synchronized clocks in our experiments to evaluate the number of packets arriving within a certain delay constraint. In order to compensate for the 20 msec clock difference between the nodes we set the codec threshold at 120 msec.

We created a Spines overlay network consisting of a fully connected graph, such that each of the 32 overlay nodes had a direct overlay link to all other nodes. Based on the latency and loss rate measured on each link, Spines selected the routing paths that minimize the *expected latency* metric presented in Section IV-B.

We then sent traffic consisting of 4 voice streams from each node to all the other nodes, in pairs, such that at any time there was only one node sending packets to only one receiver node. Each voice stream was sending a total of 2000 packets. At the same time, and between the same pair of nodes, we sent equal traffic consisting of 4 voice streams directly via UDP, using point to point connections between sender and receiver. This way, dynamic variations of loss and latency in the network affected equally the UDP streams and the streams sent through the Spines overlay. In addition to the underlying Planetlab losses, we generated 5% additional loss on each overlay link and also on each UDP stream by dropping packets at each node, just before processing them. As we ran our experiment on 32 nodes, with 8 voice streams running simultaneously between each pair of nodes, there were a total of 992 sender-receiver combinations, and the combined traffic between the

sender and receiver at any time during the experiment was 512 Kbps.

For each UDP and Spines stream we counted the number of *lost* packets and the number of *late* packets (arriving at destination after more than 120 msec). Based on these we computed the packets *missed* by the codec as the sum of both *lost* and *late* packets. Figure 16 presents the cumulative distribution function (CDF) of the *lost* packets over all streams (i.e. the percentage of streams that lost less than a certain percentage of packets). We first notice that about 50% of the UDP streams experienced only the 5% loss we injected, the rest of the streams being highly affected by underlying Planetlab loss. In contrast, the large majority of Spines streams were able to recover most of the losses. As the underlying loss increases, for about 5% of the streams, Spines could not improve the delivery ratio over UDP. We believe this is due to the loss nature of highly CPU loaded Planetlab nodes - in long bursts and happening at the end nodes. In Figure 17 we present the CDF of *missed* packets that could not be decoded by the voice codec, either because they were lost or because they arrived in more than 120 msec. Even though our testbed was confined to the North American Continent, with delays well below the 120 msec codec threshold, we see that many of the packets received by the UDP streams arrive late; the number of missed packets being considerably higher than the number of lost packets. Spines streams were able to deliver more packets than UDP in time in almost all cases, until the

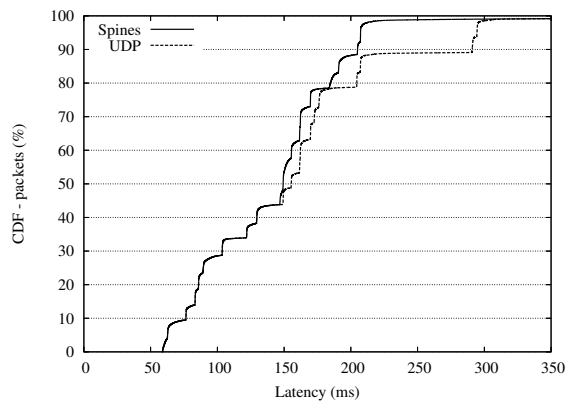


Fig. 18. Planetlab Inter-Continental - percentage of packets that arrive earlier than a certain latency

loss rate became very high (20%) and CPU scheduling delays equally affected Spines and UDP streams.

TABLE II
PLANETLAB SITES - INTER-CONTINENTAL

1.	University of Washington (USA)
2.	RNP - Rio Grande do Sul (Brazil)
3.	Swedish Institute of Computer Science (Sweden)
4.	KAIST (Korea)
5.	Monash University - DSSE (Australia)

We evaluated the benefit and robustness of our protocols on large networks that span multiple continents through a second experiment. We selected five sites in Planetlab, each one on a different continent. The sites are shown in Table II. The network latency between the sites was fairly large, ranging between 59 ms (University of Washington to KAIST) and 290 ms (RNP to KAIST). Given the high latency between the sites, the VoIP quality is heavily affected, and any reduction in packet delay is critical for improving the interactivity of conversation.

We connected all sites in a Spines overlay network where each node had direct links to all other nodes, and used the *expected latency* metric for routing inside Spines. We sent VoIP traffic from every site to all other sites, in pairs, both using UDP and Spines, similarly to the previous experiment. Between every pair of nodes, Spines and UDP streams were run simultaneously. As the latency was relatively high, the Spines real-time recovery protocol was not able to recover any of the lost packets, and therefore we observed almost identical loss rates for Spines and UDP streams. However, Spines was able to improve packet latency by using indirect routes that offered lower latency compared to the end-to-end path provided by Internet routing.

Figure 18 shows the CDF of the packet latency for all streams. First, we can see that fewer packets have high latency when using Spines, compared with UDP. The most significant latency improvement happens for the slowest 10% of the packets, which achieve a latency of about 190 ms when using Spines, compared with about 290 ms when using UDP. The reason is that streams between RNP to KAIST were routed

by Spines through the node at University of Washington, to which both sites had better connectivity compared to their direct link. This result indicates the ability of Spines to adapt to the topology and find alternate routes that improve VoIP quality. We also notice in Figure 18 that when Spines could not improve latency by routing through alternate routes, the overhead of using Spines nodes was minimal. Both UDP and Spines packets arrived with almost identical latency.

VI. INTEGRATION WITH THE CURRENT INFRASTRUCTURE

Given the large installed base of VoIP end clients and the even larger planned future deployments it is imperative that our system integrates seamlessly with the existing infrastructure. We explain what are the necessary steps to achieve this in the rest of this section.

The first component of the integration has to do with how VoIP clients are able to find their closest Spines server. We assume that each domain that wants to take advantage of the benefits provided by our system will deploy a Spines node as part of their infrastructure. In this case VoIP clients can use DNS SRV [21] records to locate the Spines node that is serving their administrative domain. This DNS query will return the IP address of (at least one) Spines node that can serve as their proxy in the Spines overlay. Once this node is found the VoIP clients can communicate with it using the interface we described in Section III-A. Then, the VoIP clients have to direct media traffic to flow through the Spines network rather than directly over UDP.

We have two proposed solutions for this issue: one that requires changes to the end-clients and one that does not. We begin with the solution that requires “Spines-enabled” clients. In the current architecture, the Session Initiation Protocol (SIP) [22] is used as a signaling protocol so that the two communication endpoints can negotiate the session parameters, including the IP address and ports that each client is waiting to receive media traffic on. A Spines-enabled VoIP client announces its capability using the *parameter negotiation* feature that is part of SIP, within the initial INVITE SIP message. The VoIP client includes in the same INVITE message the IP address and the *Virtual Port* that its Spines server is waiting to receive media traffic for the client. If the peering VoIP client is also Spines-enabled it will reply positively and include in its reply the address and *Virtual Port* at its own server. On the other hand, if the peer is not Spines-enabled it will return an error code indicating to the session initiator that it will have to revert to a “legacy” session. If the SIP negotiation was successful using Spines, each source will send media traffic through its local Spines server towards the Spines server indicated by the peer client. As the traffic is forwarded through the overlay network, the egress Spines node will finally deliver it to the destination VoIP client.

RTP [23] and RTCP data is sent seamlessly through the Spines network, offering the end clients information about the network conditions along the overlay path they use.

While this first solution is *architecturally pure*, it requires changes to the end clients which may not be initially possible. In this case, we propose to use a solution similar to the

NAT-traversal in SIP [24]. Specifically, Spines nodes will be required to intercept SIP INVITE messages and change the IP address and ports to point to themselves rather than to the VoIP clients. This way all the media traffic will flow through the Spines network which will eventually deliver it to the end-hosts.

VII. RELATED WORK

Our goal in this work is to reduce the effect of Internet losses on the quality of VoIP traffic. We do so by using an overlay network that attempts to quickly recover lost packets by using limited hop-by-hop retransmissions and an adaptive routing algorithm to avoid persistently lossy links. In this respect our work is related with techniques that try to reduce the loss rate of underlying Internet paths and with other work in overlay networks.

Multi Protocol Label Switching (MPLS) [25] has been recently proposed as a way to improve the performance of underlying network. This is done by pre-allocating resources across Internet paths (LSPs in MPLS parlance) and forwarding packets across these paths. Our system is network agnostic and therefore does not depend on MPLS, but it can leverage any reduction in loss rate offered by MPLS. At the same time, MPLS will not eliminate route and link failures or packet loss. Since it runs at a higher level, our overlay network can continue to forward packets avoiding failed network paths. Forward Error Correction (FEC) schemes [26] have also been proposed as a method of reducing the effective loss rate of lossy links. These schemes work by adding redundant information and sending it along with the original data, based on the feedback estimate of loss rate given by RTCP, such that in case of a loss, the original information (or part of it) can be recreated. Most of the VoIP solutions today (including the G.711 codec we use in this paper) use some form of FEC to ameliorate the effect of loss. Given the occasional bursty loss pattern of the Internet, many times the FEC mechanisms are slow in estimating the current loss rate, and therefore we believe that localized retransmissions are required for maintaining voice quality. Moreover, since our approach increases the packet delivery ratio, FEC mechanisms will notice a considerable reduction in loss, and therefore reduce their redundancy overhead.

Overlay networks have emerged as an increasingly growing field over the last few years, motivated mainly by the need to implement new services not supported by the current Internet infrastructure. Some of the pioneers of overlay network systems are X-Bone [27] and RON [17], which provide robust routing around Internet path failures. Other overlay networks focus on multicast and multimedia conferencing [28][29]. Our work uses the same basic architecture of an overlay network but it is optimized towards the specific problems of VoIP traffic. In [30], Tao et al present a practical solution to improve VoIP quality by using application driven path-switching gateways (APS) located at the edge of the access networks, between the end-hosts and the Internet. The APS gateways constantly monitor end-to-end network conditions over multiple paths and choose the the optimal path according

to specific application characteristics such as the codec used or type of PLC. Since the approach uses end-to-end traffic analysis to optimize performance, it is complementary to our work. We believe that it can transparently use our Spines overlay architecture between the APS gateways to improve end-to-end packet delivery ratio by exploiting our multi-hop routing and local recovery mechanisms. Finally, OverQoS [31] is probably closest to our work, as it proposes an overlay link protocol that uses both retransmissions and FEC to provide loss and throughput guarantees. OverQoS depends on the existence of an external overlay system (the authors suggest RON as an option) to provide path selection and overlay forwarding. In this respect, our system can use OverQoS as a plug-in module as an alternative to our real-time recovery protocol presented in Section IV-A, probably with the necessary modifications that take into account the special requirements of voice traffic.

VIII. CONCLUSION

In this paper we have shown that current network conditions can significantly affect VoIP quality, and we proposed a deployable solution that can overcome many of these conditions. Our solution uses the open source Spines overlay network to segment end-to-end paths into shorter overlay hops and attempts to recover lost packets using limited hop-by-hop retransmissions. Spines includes an adaptive routing algorithm that avoids chronically lossy paths in favor of paths that will deliver the maximum number of voice packets within the predefined time budget. We evaluated our algorithms and our system implementation in controlled networking environments in Emulab, on the Internet using the Planetlab testbed, and through extensive simulations on various random topologies. Our results show that Spines can be very effective in masking the effects of packet loss, thus offering high quality VoIP even at loss rates higher than those measured in the Internet today.

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