Abstract
Both Bluetooth and 802.11b wireless devices operate in the same frequency range. Increasingly, Voice-over-IP (VoIP) traffic is being routed over wireless network segments where packet loss can be an issue. This paper presents the results of a study of the effects of Bluetooth devices on the quality of VoIP calls over 802.11b networks.

Keywords
Bluetooth, 802.11b, VoIP, interference, empirical, wi-fi, speech quality, vocoder, wireless networking.

INTRODUCTION
Low-cost telephone services have traditionally been difficult to find. Because compressed speech can take up very little bandwidth, researchers have investigated the Internet as an inexpensive means to support telephone calls. Voice-over-IP (VoIP) is one result of this effort.

However, using the Internet as a telephone service can be problematic. Real-time voice communications has two main issues: reliability and latency. Telephone service that cuts out frequently in the middle of a conversation is very difficult to use, and connections with an end-to-end latency of greater than 150 ms [3] are not recommended for high-quality voice applications. Both of these issues are very serious with the Internet - there are no guarantees that packets will ever arrive at their destination, and they can arrive in the wrong order and with varying delays.

It is difficult to address both issues simultaneously. For example, Transmission Control Protocol (TCP) retransmits all dropped packets and is thus very reliable, but requires a large buffer that introduces an unacceptable latency overhead into the connection. VoIP calls use User Datagram Protocol (UDP) packets instead, because of their lower latency. Unfortunately, UDP has reliability problems, because lost UDP packets are never resent.

Increasingly, VoIP calls are being routed over wireless network segments. However, wireless networks are prone to interference, which can significantly increase packet loss. Interference is especially widespread in medium-range 802.11b networks because their frequency space - the 2.4 GHz band, extending from 2400 to 2483.5 MHz in the US - is quite crowded. Microwave ovens, cordless phones, and other wireless networking schemes all coexist in this unlicensed band.

One of the most difficult challenges for 802.11b networks is operation in close proximity to Bluetooth devices. Bluetooth is a wireless networking standard that is intended for short-range cable replacement, rather than medium-range networking like 802.11b. Since it is a complimentary standard to 802.11b, it is feasible that both Bluetooth and 802.11b devices would be active at the same time. Bluetooth uses Frequency-Hopping Spread Spectrum (FHSS) to distribute itself over the 2.4 GHz band. Under certain conditions, it can cause high levels of packet loss on an 11 Mbps 802.11b link, which uses Direct Sequence Spread Spectrum (DSSS).

This study investigated how Bluetooth interference affects the quality of a VoIP call being sent over an 802.11b link.

TEST SETUP
We configured a simple wireless network - one 802.11b-equipped laptop associated with one access point. The access point was connected to a 10 Mbps Ethernet hub. Also connected to the hub was a desktop computer (see Figure 1).

Figure 1. Diagram of setup for audio quality testing (wireless condition).
To characterize the usability of a VoIP call over the 802.11b link, we took voice quality measurements under sixteen different conditions. The signal level of the 802.11b link was varied from -75 dBm to -85 dBm (in 5 dB steps) by using RF-absorbent material and metal objects to attenuate the signal from the access point to the laptop. The average noise floor was -95 dBm, so the corresponding SNRs of the link were 20 dB, 15 dB, and 10 dB.

All mentions of the SNR of the 802.11b link refer to the SNR measured before Bluetooth interference was activated.

The signal levels used are low enough to be affected by Bluetooth interference [2], but high enough to support a stable network connection. At each signal level, voice quality tests were run without Bluetooth interference, and then with one, two, three, and four Bluetooth interferers active.

Additionally, we measured the quality of a VoIP call over a wired Ethernet link between the desktop and laptop (see Figure 2). The results from that test were used as a basis of comparison for our other results.

To create a VoIP connection, external VoIP devices were attached to the laptop and the desktop machines. The VoIP devices sample and compress an analog audio source connected to their inputs. The computers, running VoIP software, packetize the data from the VoIP device and send it over the network to its destination. Although the VoIP link established for the testing was bi-directional, the experiment focused on sending audio from the desktop to the laptop.

The devices used the H.323 setup protocol, and the G.723.1 vocoder at 5.3 Kbps. Although G.723.1 also specifies a 6.3 Kbps data rate, this mode was not supported by the hardware, and therefore was not tested. The vocoder uses 30 ms frames and specifies a method for frame-erasure concealment [4]. Because missing frames are interpolated whenever possible, higher packet loss rates (and therefore higher levels of interference) can be tolerated by this vocoder [6,7].

Audio Quality Measurement

The VoIP devices originally used low-quality headsets, consisting of a condenser microphone and earbud speaker, to record and play back sound. However, these headsets were replaced with connections to a third computer's soundcard. Because the VoIP devices put a DC bias (-3 V) on the microphone signal pin, a 470 pF blocking capacitor was used in series with the input signal. This value was large enough so that only trivial signal attenuation occurred within the frequency range of interest. The capacitor and all cables used in the experiment were shielded.

To test each VoIP link, forty different test sequences were transmitted and recorded. A third computer, called the "audio computer," provided input to the VoIP device attached to the desktop. Simultaneously, a recording of this input signal and the output from the VoIP device attached to the laptop was made (see Figure 3). In this way, we obtained forty input-output pairs from the VoIP system for each set of interference conditions. An in-house piece of software, Audio Play, Record, and Estimate (APRE), was used to perform this part of the testing.

Audio Computer

VoIP Device

Network

Figure 3. Audio signal block diagram.

Each sentence was recorded monaurally with a sampling rate of 8 kHz. The sentences were taken from a list of Harvard phonetically balanced sentences [1] to ensure that a wide variety of phonemes were represented. Half of the sentences were spoken by males and half were spoken by females.

Ideally, a large group of test listeners would evaluate the quality of the output speech. However, it was impractical to perform statistically valid human testing of the degraded audio signals — in our study, quality measurements of over 600 test signals were used. Several algorithms have been developed that can, with a high degree of accuracy, emulate a human's perception of speech quality on the Mean Opinion Score (MOS) scale. The Perceptual Evaluation of Speech Quality (PESQ) algorithm [5] is the current ITU-T recommendation (P.862) for speech quality assessment. Its MOS values correlate well with human test results, even for tricky cases such as variable-delay VoIP calls [5,8].
The PESQ algorithm was applied to each input/output pair in order to generate a MOS for that pair of sentences. The median and middle 50% range of the resulting forty MOSs were computed. The mean MOS was not used for comparison because it is easily influenced by a few extreme results.

The value of a MOS ranges from 1 to 5, with the corresponding English descriptions 'bad,' 'poor,' 'fair,' 'good,' and 'excellent.' A score of 4 is considered 'toll quality,' and is the goal of most commercial VoIP implementations.

**Bluetooth Interference**

To create Bluetooth interference, we acquired four pairs of Bluetooth transceivers and installed them in other computers. A file transfer was set up between a pair of transceivers to simulate Bluetooth activity and to create a constant source of interference. The Bluetooth transceiver sending the file was placed 1 m away from the laptop's 802.11b radio. Up to four interferers could be created in this manner.

The 802.11b radios in the access point and laptop transmitted at 15 dBm, and the Bluetooth transceivers had a maximum power output of 4 dBm. All power-saving and encryption features were disabled to allow the devices to perform at their full speed.

**MEASUREMENTS AND RESULTS**

As stated earlier, two sets of experiments were performed. First, the quality of a VoIP connection over a wired network was examined. These results formed the baseline to which our other results were compared. Second, we moved to a wireless network and observed how the voice quality was affected by the SNR of the network and the level of Bluetooth interference.

**Wired (Control) Results**

The MOSs for the quality tests performed over a wired (10 Mbps Ethernet) network exhibited little variation (see Figure 4). The middle 50% of the dataset covered a range of just 0.13 MOS points, with the median at 3.13. Although there were outliers as low as 2.66 and as high as 3.44, the results were well concentrated about the median.

We believe that at least one of the lowest outliers in each test was due to packet capture software that was running on the laptop and desktop computers during the testing. Because it was activated just moments before the first sentence was played, it caused the computers to drop a number of packets at the very beginning of each test. After that initial burst of packet loss, however, the packet capture software did not influence the speech quality. The median and middle 50% range were not significantly affected.

**Wireless Results**

Speech quality over the 802.11b network varied greatly with the signal level of the network and the number of active Bluetooth interferers (see Figure 5).

With no interference, the distributions of MOSs at 20 dB and 15 dB were almost identical, and they compared favorably with the speech quality from the wired network test. However, the 50% ranges were slightly larger, 0.16 and 0.15 MOS points respectively. The tops of the middle 50% ranges were lower by 0.02 MOS points (a negligible difference), and the medians were both at 3.12.

Even without any Bluetooth interference, the results at 10 dB showed quality degradation. The median MOS was 2.88, 0.25 points below the wired score.

With one or two interferers active, the middle 50% ranges for 20 dB and 15 dB almost completely overlapped. Although the median MOSs for the 15 dB measurements were slightly higher, the large amount of overlap indicates similar voice quality at the two signal levels.
When three or four interferers were activated, the 20 dB SNR showed a clear advantage. There was almost no overlap of the 50% ranges for 20 dB and 15 dB – the higher SNR produced significantly better scores.

The quality of speech sent over the 10 dB network lagged behind both of the other measurement categories when Bluetooth interference was present.

A significant drop in quality from the baseline wired results occurred when two or more Bluetooth interferers were activated and the SNR was 15 or 20 dB, or when any Bluetooth interference was present with an SNR of 10 dB.

CONCLUSIONS
Without Bluetooth interference, it appears that most 802.11b links can support VoIP traffic with very little quality loss. We encountered a drop in quality only when testing with an SNR of 10 dB, and even then the median MOS dropped by just 0.25 points from the wired results.

The loss of voice quality became more of an issue as the Bluetooth interferers were activated. With two Bluetooth devices actively transmitting, the quality of the 15 dB and 20 dB links dropped below the quality of the no-interference 10 dB link. As more interferers were activated, the quality quickly dropped into the range of uselessness.

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REFERENCES