Using Bluetooth for Short-Term Ad Hoc Connections Between Moving Vehicles: A Feasibility Study

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***Abstract* – Bluetooth™ is a promising wireless technology designed for short-range ad hoc connections, which has many potentially useful applications. One such use is the transfer of data between two fast-moving vehicles such as automobiles. In this paper we explore the suitability of Bluetooth to make connections in highly mobile environments. In particular, we have developed a hardware testbed to make an empirical analysis of the time it takes to establish Bluetooth connections and the range at which those connections can be established. We also explore, by means of simulation, ways in which to improve connection setup times and the impact this will have on any potential data transfer.**

I. Introduction

Imagine if, while behind the wheel of an automobile, a driver were able to obtain information about her surroundings via a wireless connection - e.g. real-time traffic information, nearby restaurants or other services. The Bluetooth standard has been suggested and studied as a potential solution for similar automotive scenarios [1, 2]. However, since Bluetooth has both limited range and bandwidth, this highly mobile environment raises serious questions about the length of time it takes to make a connection between two Bluetooth devices. If this connection setup takes too long, then either no connection will be made, or there will not be enough time to do any useful data transfer. In addition, the mobile environment presents other obstacles, such as fading, multipath and Doppler effects.

TABLE 1
Effect of Speed on Class 1 (20dBm) Devices

Vehicle Speed		Max Time
km/hr	m/s	"In Range" (s)
20	5.56	36.00
40	11.11	18.00
60	16.67	12.00
80	22.22	9.00
100	27.78	7.20

Table 1 shows some simple speed calculations for a Class 1 (20dBm) device using a nominal range of 100m as provided in the Bluetooth specification. In these examples, one Bluetooth device is moving at a constant speed, and the other is stationary. Since our application involves outdoor transmissions occurring at high speeds, we assume that a Class 1 Bluetooth device (100m range) will be necessary.

Previous investigations into Bluetooth links have suggested 2 seconds as a typical setup time between two unknown devices [1], although some experiments have shown much higher values of 10s and greater (for unknown reasons) [3]. A quick read of the Bluetooth specification [4], indicates that 2 seconds is a reasonable number, and that 10s should be an absolute maximum. It is clear from the calculations in Table 1 that a lengthy connection setup time will severely inhibit Bluetooth's usefulness in short-term ad hoc connections between two rapidly moving objects.

Our objective in this paper is to empirically measure the connection setup times of Bluetooth devices to determine if Bluetooth is suitable for use in a mobile environment. We present some of our experimental results and statistical analysis of Bluetooth connection times (Section II and Section III). In addition, we will determine through simulations if there are ways in which to modify the inquiry process to decrease the time it take for Bluetooth devices to discover other Bluetooth devices (Section IV and Section V). Finally, we will provide some analysis and concluding comments about the future of Bluetooth in a highly mobile environment.

II. Experiment Description

We present the results of two types of experiments here. The first is a characterization of the time it takes to setup and establish a Bluetooth connection among a group of static devices. The second is a classification of the range in which Bluetooth devices can establish connections and the data transfer rates that can be achieved at a given range.

A. *Device Discovery Characterization*

One limiting factor in the amount of data that can be transferred over a Bluetooth connection in mobile

environments is the amount of time spent discovering other devices and establishing connections. The Bluetooth specification provides for a negligible delay in establishing connections to devices, which have been previously discovered. As a result, we designed three experiments to characterize Bluetooth's device discovery process. The first measures how many Bluetooth devices can be discovered in a short, fixed amount of time. The second measures the latency in receiving the first reply to an inquiry. The final provides a distribution of discovery times for the individual devices used in these experiments.

Our hardware testbed consists of five Bluetooth devices from various manufacturers:

- Two Ericsson Bluetooth modules with Class 2 radios each hosted by a Linux-based embedded systems development board made by Axis Communications
- Two Texas Instruments Bluetooth modules with Class 1 radios each hosted by Windows 2000 PC's
- One Toshiba Bluetooth PC Card with a Class 1 radio hosted by a Windows 98 laptop

We chose one of the Ericsson modules, hosted by the Axis development board, to act as the inquirer in these experiments. The software used in this system is an open source implementation of the Bluetooth stack [5]. We were able to use this stack to interactively issue device discovery requests and to accurately time the responses. By including a variety of different Bluetooth devices in this test, we can see, for short-range communication, whether the device discovery and connection setup times are independent of radio power and manufacturer.

B. *Range and Throughput*

A second limiting factor of Bluetooth's suitability in mobile environments is its performance at non-negligible distances. Two aspects of this performance are important here: the range over which devices can establish and maintain connections and the data transfer rate possible a given distance. We designed two experiments to investigate these aspects of Bluetooth's performance. The first measures the distance at which two Bluetooth devices can successfully discover one another and establish a connection. The second explores the data transfer rates that can be achieved at distances within the maximum range established by the first experiment.

For these two experiments, our hardware testbed consists of Class 1 and Class 2 Bluetooth modules based on SiliconWave chipsets. The same Linux-based development boards mentioned above hosted these modules. The modules were connected to the development boards serially through our own custom hardware. The Bluetooth radios in these experiments communicate via antennas manufactured by GigaAnt. These are omnidirectional, passive, half-wave antennas designed specifically for 2.4GHz applications.

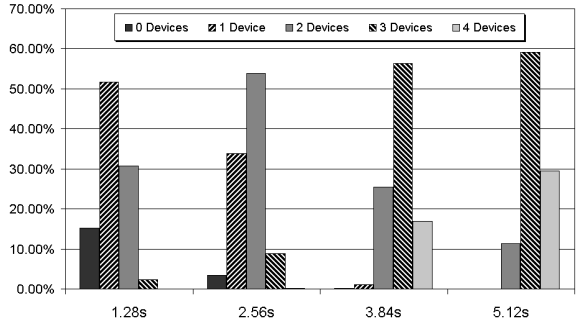

Fig. 1. Number of Devices Discovered

Throughout these experiments, the Bluetooth devices were in an open-air, line-of-sight environment far from any potential interference. The throughput tests were run in this setup by repeatedly timing FTP transfers between connected devices.

III. Experimental Results

A. *Device Discovery Characterization*

Fig. 1 shows the results of our first experiment. In this test, we set up one device as an inquirer with the remaining four acting as inquiry targets. We were able to set timeout on the device discovery, but the HCI layer interface fixes this value at multiples of 1.28s. We ran each test 3384 times. In the case of the 1.28s test, we see that at least one device is discovered 84.78% of the time. In the 2.56s test, no devices are discovered only 3.40% of the time.

TABLE 2
Length of First Connection Establishment

Number of Tests	Mean Inq. Time (s)	Median Time (s)
1142	0.79	0.53

In our second experiment, we set the inquirer to stop after it had received the first reply. Table 2 and Fig. 2 show the results of this test. When there are multiple Bluetooth devices to be discovered, the first connection occurs quite quickly. In addition, we found that the connections were distributed evenly among the four

devices, so that no device was more likely to establish the first connection repeatedly.

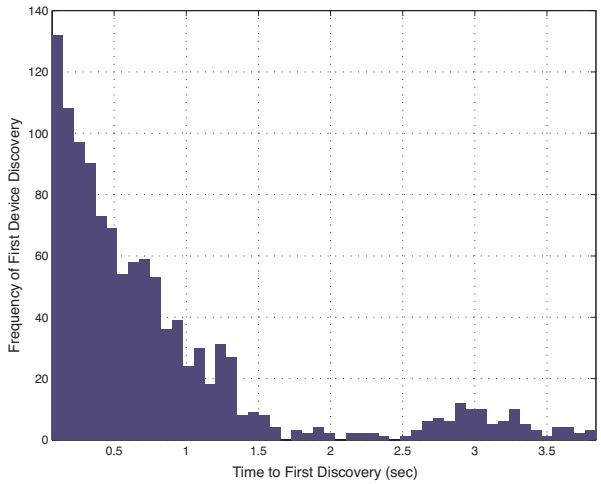

Fig. 2. Time to First Device Discovery

For our final test, we measured the discovery time of each individual device. The discovery time can theoretically vary between devices if the clocks are not initially well synchronized, as can be the case in devices from different manufacturers. Table 3 shows the results. We can see from this experiment that the average connection time to an individual Bluetooth device is, indeed, around 2s, although the median is a bit lower. Furthermore, there are not tremendous variations between different Bluetooth devices.

TABLE 3
CONNECTION TIME TO 1 BLUETOOTH DEVICE

	Number of Tests	Mean Time (s)	Median Time (s)
Device 1	600	2.26	1.72
Device 2	505	2.63	1.95
Device 3	610	2.11	1.35
Device 4	499	2.10	1.36

B. *Range and Throughput*

The first task in characterizing Bluetooth's performance over large distances is to determine the maximum range over which devices can discover one another and establish connections. This is a very simple test, but the results proved surprising. Table 4 lists the results of basic range tests for the two highest power classes of Bluetooth devices. These results are surprising in that both classes of radios far outperform the minimum ranges required by the Bluetooth specification. This over-performance is a very encouraging indication of Bluetooth's feasibility for use in mobile environments.

TABLE 4
RANGE TEST RESULTS

	Maximum Range (m)	Spec Range (m)
Class 1 (20 dBm)	250	100
Class 2 (4 dBm)	122	10

The results for our final experiment are presented in Fig. 3. The thick vertical lines represent the nominal range provided by the Bluetooth specification for each class of radio. As suggested by the previous experiment, the ranges over which both classes of devices achieve effective communication far outperform the specification. The consistency of the data rates over a large range of distances is also encouraging. It should be noted that the physical interface for the devices used in our experiments is limited to a data rate of 115.2kbps, a limitation common to nearly all currently available Bluetooth devices which communicate through via UART. Also, Bluetooth automatically applies FEC coding (at a 2/3 rate in our case) to transmitted packets [4]. These two factors explain the limited maximum throughput realized in our experiments. While the realized throughput is significant less than Bluetooth's rated maximum, we believe that the trends observed in our experiments will hold for higher data rate Bluetooth devices.

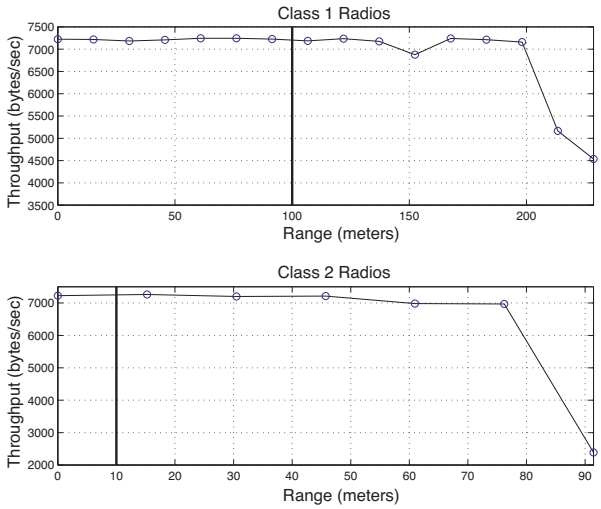

Fig. 3. Range vs. Throughput

IV. SIMULATION DESCRIPTION

The Bluetooth baseband specification [4] rigorously defines the device discovery process, the details of which we will not discuss here. After studying the device discovery process, we have isolated two factors that have the potential to dramatically affect the time

required to discover Bluetooth devices. The first factor is the use of two disjoint sets of frequencies, called frequency trains, during device discovery.

Currently in the inquiry process, a Bluetooth device alternately scans half the possible frequencies, in intervals of 1.28 seconds, on which a another Bluetooth device may reside [6]. Our experiment would be to scan all possible frequencies at the same time.

The second factor is a mandatory delay every device must wait before responding to a master's inquiry [7]. The length of this delay is uniformly distributed between 0 and 640ms. This random delay, or backoff, is designed to significantly reduce the probability of two devices responding to a master's inquiry at the same time at the same frequency (i.e. a collision). Our experimental results indicate average discovery times in dense environments of about 0.8s. Clearly, the elimination or reduction of the average 0.32s random backoff could result in a significant impact on discovery times.

Ideally, we would like to empirically explore the impact of modifications to these factors in the baseband protocol code of real Bluetooth devices. Unfortunately, only the manufacturers of Bluetooth devices enjoy access to the baseband code, which they are generally reluctant to share. As a result, we must explore the affects of changes to these factors through simulation. We developed a custom simulation environment, named RIBBIT[1] (RIce Bluetooth Baseband Inquiry Tester), to model the Bluetooth inquiry process. Using this simulator, we explored both eliminating the frequency trains in the inquiry process and shortening the random delay a device waits before responding. RIBBIT is partially based on IBM's open-source Bluetooth simulator [8].

IV. Simulation Results

Fig. 4 shows a sample of the results of these simulations. It is clear that our modifications greatly improve the time for first device discovery and the number of devices found within a given period of time. In addition, these modifications do not significantly degrade performance [6], as measured by the increase in the number of collisions. We found that by eliminating the random backoff, discovery times are significantly improved, especially in dense environments. Eliminating the frequency trains, on the other hand, offers the best performance gain in sparse Bluetooth environments [6]. Finally, these modifications do not substantially increase the number of collided inquiry responses, the mostly probable ill effect of our modifications.

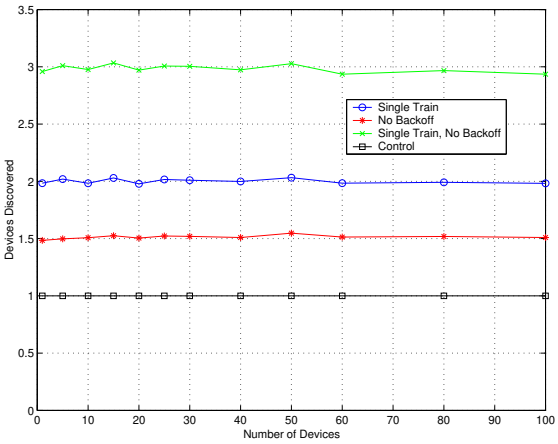

Fig. 4. Number of Devices Found in a 1 Second Search (Normalized)

More detailed results from these simulations along with a comprehensive discussion of the rationale driving this investigation are available in [6].

V. Discussion and Future Work

The results of our initial experiments are very encouraging and show that the device discovery and connection setup times for Bluetooth do not prohibit its use in applications with short times in-range. We are also extremely encouraged by the results of our range testing. Even Class 2 radios offer sufficient communication range to provide a useful time in-range between fast-moving vehicles. Table 5 presents an updated version of the information in Table 1 recalculated using our results.

TABLE 5
Recalcuation of Effects of Speed on Class 1 (20dBm) Bluetooth Devices

Vehicle Speed		Max Time
Km/hr	m/s	In Range (s)
20	5.56	90.00
40	11.11	45.00
60	16.67	30.00
80	22.22	23.50
100	27.78	18.00

We are currently expanding our hardware testbed to put real Bluetooth devices on moving vehicles. The first step in this is placing fixed Bluetooth basestations around the Rice University campus and attaching Bluetooth devices to the shuttle busses that circulate the campus. This expanded testbed will allow us to

[1] For more information about our simulator, visit the RIBBIT simulator home page at http://koala.ece.rice.edu/bluetooth/ribbit/

perform an even larger variety of connection setup, throughput and routing experiments with Bluetooth.

The simulation results are also very promising in the ability, by making some very simple modifications to the Bluetooth baseband protocol, to reduce the time it takes for Bluetooth devices to discover other Bluetooth devices. Based on our simulation data, the next step to make Bluetooth even more useful in highly mobile environments would be to perform an empirical characterization of the suggested modifications of the baseband protocol in real Bluetooth hardware. Finally, we would also like to explore more realistic channel models, with obstacles such as fading, multipath and Doppler effects, to see its effects on the Bluetooth standard.

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