Antenna Characterization for Bluetooth-based Travel Time Data Collection

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ABSTRACT

Several approaches for travel time data collection based on the reading of time-stamped media access control addresses from Bluetooth-enabled devices have been reported in the literature recently. This new approach offers a number of advantages over more conventional methods, including lower costs of hardware and software, the volume of data that can be collected over time, and ease of implementation.

A fundamental component that may affect the quantity and the quality of the travel time samples collected with a Bluetooth-based system is the antenna type utilized. Antenna characteristics such as polarization and gain must be matched to specific application environments to optimize the performance of a Bluetooth reader unit. However, experimental data that focuses on antenna characterization as it relates to the use of Bluetooth technology to assess the performance of transportation facilities is lacking.

In this study, five different types of antennas were characterized to assess their suitability to support a Bluetooth-based travel time data collection system. The results indicate that vertically polarized antennas with gains between 9dBi and 12dBi are good candidates for travel time data collection. Also, different antenna types are better suited to different uses of the Bluetooth-based system. If the main focus is the collection of travel time data, then an antenna with a lower sampling rate may provide more accurate travel time samples.

KEYWORDS

Antenna Characterization for Bluetooth-based Travel Time Data Collection

1.0 INTRODUCTION

One approach for improving mobility and the efficiency of the transportation system is to improve the operations and management of the existing transportation infrastructure. A fundamental performance measure related to mobility and transportation efficiency is travel time. Without reliable measures of performance, the management of the transportation system becomes much more difficult. Having accurate travel time estimates will also help in the evaluation of proposed highway or transit facilities.

Travel time data collection based on the reading of time-stamped media access control (MAC) addresses from Bluetooth (BT) enabled devices has been in use for several years (Wasson et al., 2008). A basic setup to collect travel time data via BT includes a reader unit and an antenna. This approach for collecting travel time data offers a number of advantages over more conventional methods, including lower costs of hardware and software, large volumes of data that can be collected over time (depends on the level of market penetration of Bluetooth technology), and ease of implementation. The latter advantage makes this data collection method suitable for temporary or permanent deployment along different types of travel corridors, including interstate highways, and principal and minor arterial roadways.

Several applications in which time-stamped MAC addresses collected from BT-enabled devices have been employed to estimate the performance of a system have been reported. Wasson et al. (2008) conducted a study in the greater Indianapolis area to estimate freeway and arterial travel times. Haseman et al. (2010) calculated travel delay times in a rural interstate

highway work zone along I-65 in Northwestern Indiana, assessed driver diversion rates, and developed proposed metrics for a state transportation agency to evaluate work zone mobility performance. Barceló et al. (2010) assessed the quality of the data collected from BT mobile devices for travel time forecasting and to estimate time dependent origin-destination (OD) matrices. Quayle et al. (2010) measured arterial travel performance (i.e., segment travel time, average running speed, and OD) in a study conducted in Portland, Oregon. Day et al. (2010) evaluated signal coordination by combining high resolution signal data with travel time measurement from BT device MAC address matching. Using this technique, optimal offsets were calculated for a Saturday plan on a four-intersection signalized corridor, and the operational impacts were estimated. Haghani et al. (2010) compared floating car data with BT sensor data and concluded that the latter can be used as "ground-truth" for evaluating other sources of travel time and other ITS applications.

1.1 Research Motivation

There are several factors that may affect the quantity and the quality of the time-stamped MAC address data collected with a BT-based system. These factors may be associated with the firmware/software implementation or with the hardware components used (e.g., the type of BT chipset). An important decision that needs to be made in the hardware category is the type of antenna to use. Antenna characteristics, such as polarization and gain, must be matched to specific application environments to optimize the performance of a BT reader unit.

Very few studies exist in the literature that have thoroughly investigated the effects of antenna properties on the accuracy of the travel time samples obtained with a BT-based travel time data collection system. Puckett & Vickich (2010) tested various configurations of antennas

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with BT readers to assess the system's effective read range. Omnidirectional antennas with gains of 1 decibel (dB), 3dB, and 5dB, and a Yagi antenna with a gain of 13dB were tested. The results showed that the most consistent capture rate was when the received signal strength index (RSSI) level sensed from BT-enabled devices was no less than -80dBm. Also, a moderate increase in the effective range (and resulting capture rate) was observed when the omnidirectional antenna with a 5dB gain was used. Malinovskiy et al. (2011) tested several antennae configurations and BT readers in a one mile long corridor and compared the detection rate error of their BT-based system versus an automatic license plate based system. Two omnidirectional antennas with gains of 7decibel isotropic (dBi) and 9 dBi, respectively, and one directional antenna with a gain of 12 dBi were tested. The directional antenna had a 35 degree vertical and horizontal half-beam width. Their results showed that a pair of BT detectors mounted on opposing sides of the roadway at each end of the corridor, one using the 7dBi antenna and the other the 9dBi antenna, resulted in the lowest error compared to the other combinations of mounting locations and antennae.

Given the small sample of prior work found and the fact that the emphasis of these studies was not to better understand the effect of antenna type, it is evident that experimental data that focuses on antenna characterization as it relates to the use of BT technology to assess the performance of transportation facilities is still lacking. Antennas are fundamental components of any wireless data collection system and do significantly affect its performance if not selected carefully. In the context of travel time data collection using BT technology, for example, the size of the coverage area defines how many times a single MAC address will be detected in a single pass. To produce MAC address matches, a decision has to be made as to

which single detections at two consecutive detectors will be used to calculate a travel time sample for a segment. This decision could bias the resulting travel time estimation error.

In this study, five different types of antennas were first characterized to understand how their main properties (i.e., polarization and gain) influence the performance of a single BT reader. Next, the five antennae were used to collect travel time samples on a 0.75 mile four-lane road segment in Salem, Oregon. The results indicate that the quantity and the quality (e.g., percentage of duplicates) of the MAC addresses read with each antenna type are different. The volume of unique MAC addresses collected during the testing period were compared to traffic volumes collected over the same time period via inductive loop detectors.

The remainder of the article is organized as follows: Section 2 explains the main components of the BT-based travel time data collection system, including the BT reader unit, antennas, and the installation locations of the BT readers for testing. Section 3 presents the experimental approach used and the results obtained from characterizing five different types of antennas with a single BT reader. Section 4 explains the experimental approach used and the results obtained from collecting travel time samples with the five different antennas types using two BT readers. Finally, section 5 presents the conclusions of the study.

2.0 BLUETOOTH TRAVEL TIME DATA COLLECTION SYSTEM

In this section, the main components of the BT-based travel time data collection system used in this study are described. The BT reader is presented first, followed by a description of the salient features of each antenna tested. The last subsection explains the characteristics of the sites where the BT reader units and antennae were installed and tested.

2.1 Bluetooth Reader

The BT reader used to collect travel time data is depicted in Figure 1. The BT reader is a fundamental component of the BT-based travel time data collection system and is capable of performing several functions, including:

- Collecting MAC addresses wirelessly from BT-enabled portable devices under a full spectrum of environmental and traffic conditions. To protect citizens' privacy, the BT reader's software removes the first five characters and the last character from the MAC addresses collected.

- Adding a time-stamp to partial MAC addresses collected so that travel time samples can be calculated.

- Storing a large quantity of partial time-stamped MAC addresses in internal memory before this information is extracted.

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Take in Figure 1

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The BT reader was assembled from commercially available components. Internally, it is equipped with an ALIX WIFI board (Ituner Networks Corporation, 2011) which provides several interfaces, including a 10/100 Base T Ethernet port for network connectivity, an external memory slot for a compact flash card, a DB9 serial port, and dual USB ports. A class 1 type external BT adapter (Sena Technologies, 2011) is connected to the ALIX WIFI board via one of the USB ports. The external BT adapter has a transmission output power of approximately 79.43

milliwatts (+19 dBm). The BT reader may be powered with a DC jack or by using a power over Ethernet (POE) injector. The ALIX WIFI board is protected by an extruded aluminum enclosure to minimize the potential of damage resulting from the accumulation of dust and/or moisture. The operating system employed by the BT reader is the Linux distribution Voyage Linux (kernel 2.6.26).

2.2 Antennas

There were two main factors considered in the antenna selection process: *polarization* and *gain*. Polarization refers to the orientation of the electric field vector in the radiated wave. For example, Figure 2a depicts the orientation of the electric field (E-field) vector for an antenna with horizontal polarization (e.g., an antenna for TV reception). This antenna will not radiate and will not receive a wave polarized perpendicular to its electrical vector (Vizmuller, 1995).

Gain is a measure of the directionality of the antenna. Antenna gain is defined as the power output, in a particular direction, compared to that produced in any direction by a perfect omnidirectional antenna (i.e., isotropic antenna). For example, if an antenna has a gain of 3dB, that antenna improves upon the isotropic antenna in that direction by 3dB or a factor of two (Stallings, 2005). Figure 2b depicts a comparison between the ideal concept of an isotropic antenna (Gain = 1) and a directional antenna with a value of gain greater than one along the horizontal axis.

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Take in Figure 2

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Five different antennas with different polarization and gain characteristics were selected for testing. Table 1 presents the most important specifications of each antenna.

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Take in Table 1

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Table 2 shows pictures of the antennas, their vertical and horizontal cross-sectional coverage patterns, and their manufacturers.

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Take in Table 2

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2.3 BT Reader Test Locations

The BT-based data collection system used in this study consisted of two BT readers located 0.75 miles apart on Oregon Route 221 (Wallace Road NW) on the west side of the city of Salem, Oregon. The posted speed limit on this road segment is 45 miles per hour. The approximate location of the BT readers on Route 221 is depicted in Figure 3.

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Take in Figure 3

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The BT reader labeled as "Reader 1" in Figure 3 was installed at a test site operated by the intelligent transportation systems (ITS) unit of the Oregon Department of Transportation (ODOT). This test site is equipped with inductive loop detectors that provide traffic flow volume data to facilitate performance assessment of other technologies that the ODOT ITS unit needs to evaluate. The BT reader labeled as "Reader 2" in Figure 3 was installed inside a control box located behind a beacon sign. Both BT readers could be accessed remotely via a cellular router. Since the BT reader installed at the beacon sign was located only 0.75 miles southeast from the BT reader installed at the test site, it was assumed that the traffic count data observed every 15 minutes was similar at both sites. Observations of traffic indicate that the number of vehicles turning off of the test segment is very low relative to the overall traffic volume.

Figure 4a and Figure 4b show examples of how the two BT readers and their antennas were installed at the test site and at the beacon sign, respectively. Antennas were mounted approximately 15 feet above the ground at both locations.

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Take in Figure 4

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3.0 ANTENNA CHARACTERIZATION DATA COLLECTION AND ANALYSIS

In this section, the experimental approach used and the results obtained from characterizing five different types of antennas to understand how their main properties (i.e., polarization and gain) influence the performance of a single BT reader are discussed. All five antennas were tested at the test site (i.e., Reader 1). The performance of the antennas was evaluated using MAC address data in conjunction with traffic volume data.

3.1 Experimental Design

The experimental design used was a single factor experiment (i.e., antenna type) with an unequal number of trials per antenna type. The order in which the five antennas were tested was randomized and the BT reader unit with a specific antenna was installed for a period of between three and seven days. The reason some antennas were tested more days than others was either because they were installed right before a weekend or because ODOT personnel were not available to assist with antenna installation. The coverage patterns of all the antennas tested covered all traffic lanes (i.e., two lanes in each direction).

The *fraction read* was the main antenna performance measure and was computed as follows:

$$Fraction\ read = \frac{Total\ unique\ MAC\ addresses\ read}{Total\ traffic\ volume\ (in\ both\ directions)} \qquad (1)$$

Both metrics used to calculate the fraction read were collected over the same test period. Also, it was assumed that the fraction of vehicles with active BT devices present was the same over the periods that each antenna was tested. This assumption was validated by comparing the performance of the same antenna for non-overlapping time periods.

In addition to the *fraction read*, the average number of reads per MAC address over the test period was computed as follows:

$$Avg.\ reads\ per\ MAC\ address = \frac{Total\ MAC\ addresses\ read\ (including\ duplicates)}{Total\ unique\ MAC\ addresses\ read} \qquad (2)$$

This measure is indicative of the total volume of data collected, and a higher *fraction read* measure combined with a relatively low average reads per MAC address measure is ideal.

3.2 Data Collection and Processing

Two data sources were utilized to characterize the performance of the antennas. The first data source was a file containing the time-stamped MAC addresses collected by the BT reader and antenna combination during the test period. A sample of the raw data collected by the BT reader unit is depicted in Figure 5. The fields of each record in the file are comma separated. The first field displays the MAC address of the mobile BT-enabled device captured by the BT reader unit; the second field displays the date; the third field displays the time; the last field displays the MAC address of the BT reader.

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Take in Figure 5

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The second data source was traffic flow volume data corresponding to the period each antenna was tested. In each lane adjacent to the BT reader (at the test site only), inductive loop detectors were present and collecting traffic flow volume data (i.e., counts for every 15 minute period).

MAC addresses whose counts were greater than 100 over the time an antenna was tested were removed, since these addresses were (very likely) not collected from passing vehicles. In some periods, the same MAC address was read thousands of time. Counts of unique MAC

addresses read by each antenna during the testing period were tabulated for the 15-minute periods used for traffic counts, so that this data could be compared to the corresponding traffic flow volume data collected.

3.4 Results

The test results showed that the quantity and the quality (e.g., percentage of duplicates) of the MAC addresses read with each antenna type were different. Table 3 presents six pieces of information for each antenna, i.e., the *fraction read*, the average number of reads per MAC address, the total traffic volume during the testing period, the average traffic volume during the testing period, the total number of hours the antenna was tested, and whether or not the testing period included the weekend (i.e., Saturday and Sunday). The antennas in Table 3 are ordered from highest to lowest with respect to *fraction read*.

The data shows that the average traffic volume along the test corridor was very consistent throughout the week. As mentioned before, the data presented in Table 3 excludes those MAC addresses that were read more than 100 times over the test period. MAC addresses whose total count was more than 100 most likely were collected from devices located inside nearby apartment/houses, pedestrians, cyclists, or parked vehicles in the vicinity of the BT reader unit.

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Take in Table 3

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A Chi-squared test was conducted to test the null hypothesis that the performance measure *fraction read* is the same for all antennas tested. This null hypothesis was rejected with

a P-value of close to zero, which indicates that differences in antenna performance do exist. The Marascuillo procedure was applied to examine significant differences with respect to the performance measure *fraction read* at a 95% confidence level between all pairs of antennas. The results are shown in Table 4 (ordered from highest to lowest with respect to *fraction read*), where a "1" in a cell indicates a significant difference in the *fraction read* between the two antennas being compared.

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Take in Table 4

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Antenna 1 (Omnidirectional) has a significantly higher *fraction read* than any other antenna, and antenna 4 with the second highest fraction read, is significantly better than all antennas except antenna 1. There is about equal performance between antennas 3 and 5, with antenna 2 having the worst overall performance. The two best performing antennas were both vertically polarized antennas, but differed in gain and the shape of their coverage pattern.

The average number of reads per MAC address varied widely among the antennas. There is no clear correlation between this measure and the polarization and gain characteristics of the antennas tested. However, the omnidirectional antenna, which had the best overall *fraction read* performance, had the third lowest average reads per MAC address. Thus, it does not appear that a better *fraction read* measure will necessarily come with an increase in data volume.

To better understand the behavior of the BT reader unit and antenna combination with respect to the performance measure *fraction read*, additional data analysis was conducted. For the purposes of modeling and data analysis, it is important to understand the characteristics of the

fraction read probability distribution. The probability that a MAC address is read from a passing vehicle depends on:

1. The probability that the vehicle contains an active BT device, and

2. The probability that the BT reader captures the MAC address from this BT device during device inquiry in the limited time the vehicle is in the antenna coverage area.

If these probabilities are consistent over time (as assumed) and reading of MAC addresses from different BT devices is independent, then the number of MAC addresses read from a given number of vehicles will be binomially distributed. If it is assumed that the number of MAC addresses read is binomially distributed, analyses and plots of the data should produce results consistent with this assumption. Figure 6 shows a plot of the fraction read for a 15 minute time period versus the traffic count for that same 15 minute time period for antenna 4 (i.e., Yagi antenna). Assuming the overall fraction read is equal to the probability that a MAC address is read from a passing vehicle, the dotted black lines in Figure 6 represent +/- two standard deviations from the expected fraction read.

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Take in Figure 6

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Approximately 94% of the fraction read values plotted in Figure 6 fall within +/- two standard deviations from the expected fraction read. Under the binomial assumption, approximately 95% of the fraction read should fall within +/- two standard deviations from the

expected fraction read. Other antennas produced similar results with slightly lower percentages within +/- two standard deviations from the expected fraction read except antenna 5, which displayed much higher variability over time.

One critical assumption made is that the fraction of vehicles with active BT is constant. To provide additional evidence that the fraction of vehicles containing active BT devices does not fluctuate significantly over time, Chi-squared tests were applied to test the null hypothesis that the *fraction read* is the same for non-overlapping 24 hour time periods using the same antenna. Since the antenna type stays the same, differences in the performance measure *fraction read* may be attributed to differences in the fraction of BT devices in vehicles passing the BT reader unit. This null hypothesis was clearly rejected for antenna 5, which displayed much higher variability over time. The P-value for this statistical test for antenna 1 was 0.033, and was greater than 0.05 for all other antennas except antenna 5 (i.e., the null hypothesis for antenna 1 would be rejected at a 95% confidence level but not at a 97% confidence level, and the null hypothesis would not be rejected at a 95% confidence level for antennas 2, 3, and 4).

4.0 COLLECTION AND ANALYSIS OF TRAVEL TIME SAMPLES

In this section, the experimental approach used and the results obtained from collecting travel time samples with different types of antennas are discussed. In this part of the study, all five antennas were tested using the two BT readers installed along Oregon Route 221.

4.1 Collection and Processing of Experimental Data

Both BT readers were equipped with the same antenna type and collected MAC addresses for two separate periods of between three and seven days. The reason for the different testing durations is the same as mentioned in section 3.1.

The order of the tests was randomized. During the same periods that the antennas were tested, probe vehicle runs were also conducted. Each of the five antenna types was tested twice on Oregon Route 221 and 20 probe vehicle runs were conducted by two drivers in a single day within each testing period, for a total of 10 days worth of probe vehicle runs (or 200 probe vehicle runs). The probe vehicles runs were used to assess the accuracy of the travel time estimates computed from the data collected by the two BT readers. The probe vehicle contained an active BT device with a known MAC address and a clock synchronized with the BT readers. The time that the probe vehicle passed each BT reader was recorded. A line drawn from the BT reader and perpendicular to the road was used as the location where the vehicle passed the BT reader.

For each time period that a specific antenna was tested, the following performance measures were computed:

- Traffic volume.

- The number of travel time samples computed from the collected data.

- The percentage of travel time samples obtained with respect to traffic volume.

- The average percent difference in travel times (between BT reader 1 and BT reader 2) between the probe vehicle and the travel times computed for the probe vehicle from collected MAC address data.

- The average *absolute* percent difference in travel times (between BT reader 1 and BT reader 2) between the probe vehicle and the travel times computed for the probe vehicle from collected MAC address data.

4.2 Computing Travel Time Samples from MAC Address Data

The general procedure for computing travel time samples from collected MAC address data implemented in software consisted of the following steps:

1. Identify all MAC addresses detected by each BT reader.

2. Eliminate those MAC addresses not detected by both BT readers.

3. For data from a single BT reader, organize the MAC address data into "groups."

4. Compute travel time samples from the groups of MAC addresses for each BT reader.

A *group* is defined as a collection of data records with the same MAC address sorted sequentially by time, where the time between any adjacent records is no greater than a fixed threshold. Groups of MAC addresses are defined for individual BT readers and they represent the number of times a single MAC address was captured as a vehicle traveled through the BT reader's antenna coverage area. For this analysis, 30 seconds was the time threshold defining a group. This value is less than the smallest reasonable travel time between the BT readers located on Oregon Route 221 and greater than the time a vehicle traveling at the speed limit would be in the coverage area of an antenna. Three times were obtained for each MAC address group. These were the earliest, latest, and average of the earliest and latest times in the group (referred to as the *average group time*). Examples of these times are depicted in Figure 7. It is possible (and was seen frequently) for a group to consist of a single record. In this case, the earliest, latest, and average of the earliest and latest times were all the same time.

Take in Figure 7

To compute travel time samples from groups of MAC addresses, a second threshold value of two minutes was utilized. This threshold value was the maximum time difference between the average group times. The two minute threshold worked well since there was little or no congestion on Oregon Route 221 and two minutes is the approximate time to complete a round trip passing both BT readers twice. Two groups that exceeded this threshold were not used to compute travel time samples. This prevented the generation of extremely large travel time samples from groups of the same MAC address occurring on different days, or on different trips for the same vehicle in the same day.

4.3 Results

Results for the percentage of the traffic volume for which a travel time sample was obtained (i.e., the *sampling rate*) are shown in Table 5. With the exception of antenna 4 (i.e., Yagi), this percentage was very consistent for the same antenna type over different time periods, which indicates that uncontrollable factors such as climatic conditions and interference from unknown sources had little impact on antenna performance. The performance of antenna 4 is sensitive to orientation and inconsistencies in this installation parameter may have contributed to the differences seen over different time periods. The antennas in Table 5 are ordered from highest to lowest with respect to *weighted average percentage match*.

The results indicate that antenna 5 is clearly the best performing antenna *with respect to generating travel time samples*. Antenna 4 also performed well, but showed inconsistencies over time periods which are not well understood.

While a high sampling rate value is desirable, the accuracy of the collected travel time samples is perhaps a more critical performance measure. When computing travel time samples from groups of MAC addresses, different methods for computing samples exist that differ in what time stamp in a group of MAC address is utilized. The following five methods were examined:

1. BT reader 1 Group Average Time – BT reader 2 Group Average Time

2. BT reader 1 Group First Time – BT reader 2 Group First Time

3. BT reader 1 Group First Time – BT reader 2 Group Last Time

4. BT reader 1 Group Last Time – BT reader 2 Group First Time

5. BT reader 1 Group Last Time – BT reader 2 Group Last Time

Table 6 shows the accuracy results of travel time samples obtained using the *most accurate method* for an antenna type during its corresponding testing time period. Accuracy was determined by comparing the estimated travel time derived from MAC addresses to the average travel times recorded by the probe vehicle for each antenna during the testing period. Both the average errors and average absolute errors (shaded rows in Table 6) were computed as the percent difference from the manually recorded probe vehicle travel times. The antennas in Table 6 are ordered from highest to lowest with respect to the response weighted average percentage match.

The most accurate method for computing travel time samples was to utilize the difference in *average* group times. The other methods generated much larger average errors. The lowest error percentage was generated by antenna 2. This antenna also had the lowest sampling rate.

Figure 8 shows that a trade-off exists between the sampling rate and the accuracy of the travel time samples collected. This is attributed to differences in the road coverage area realized by the different antenna types.

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Take in Table 5

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Take in Table 6

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Take in Figure 8

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5.0 CONCLUSIONS

In this study, five different types of antennas were first characterized to understand how such properties as polarization and gain influence the ability of a single BT reader to capture time-stamped MAC addresses from BT-enabled devices contained in passing vehicles. The performance of the antennas was evaluated using MAC address data collected during the testing period that was compared to traffic volumes collected over the same time period via inductive loop detectors. The results showed that the quantity and the quality of the MAC addresses read with each antenna type were different. In particular, antennas 1 and 4 (both vertically polarized) were significantly better with respect to the performance measure fraction read than the other three antennas. On the other hand, antennas 2 and 1 were the best performers with respect to the average reads per MAC address. It was anticipated that antenna 1 (an omnidirectional antenna) would collect a higher percentage of "redundant" MAC addresses than those with more directionality, but this was not the case. However, this result is specific to our study and cannot be generalized. In summary, vertically polarized antennas with gains between 9dBi and 12dBi are good candidates to support a BT-based travel time data collection system. Antennas with circular polarization did not seem to improve performance, despite the lack of control that designers have over the orientation of BT-enabled devices in most applications.

The results of utilizing different antennas to read MAC addresses at two locations on a 0.75 mile four-lane road segment in Salem, Oregon, and computing travel time samples from this data indicate that a trade-off exists between the number of samples obtained and the accuracy of these travel time samples. This trade-off is attributed to differences in road coverage areas provided by the different antenna types. A large area generates large groups of MAC addresses that are multiple reads of the same MAC address while a vehicle is moving in the antenna

coverage area. It is not apparent from the data which record within a group best represents the point at which the vehicle is closest to the BT reader. This highlights the importance of developing methods to filter MAC address data effectively. If this can be performed effectively, then ideally only the MAC address records that represent the time a vehicle is the closest to the BT reader will be used to compute travel times.

The results also indicate that different antenna types will be suited to different uses of the BT readers. If the main focus is the collection of travel time data, as in this research, a lower sampling rate (smaller coverage area) combined with more accurate travel time samples may be desired.

6.0 ACKNOWLEDGMENT

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Table 1

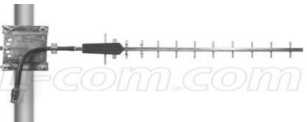|	Antennas				
	1	**2**	**3**	**4**	**5**
Directionality	Omni	Directional	Directional	Directional	Directional (Wide Pattern)
Frequency Range (MHz)	2400-2500	2400-2500	2400-2485	2400-2483	2400-2483
Polarization	Linear Vertical	Dual (both vertical and horizontal)	Right Hand Circular	Linear Vertical	Linear Vertical
Maximum Gain (dBi)	9	11	12	12	8.6

Table 2
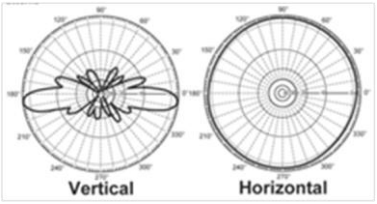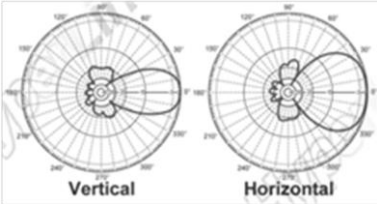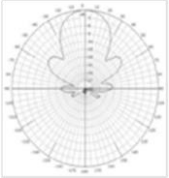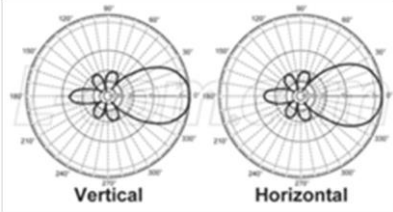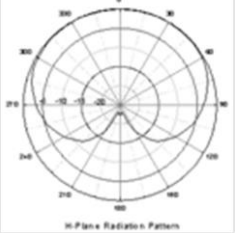
Antenna	Picture	Antenna Coverage Patterns	Manufacturer
1			L-com, Inc., Antenna model #: HG2409UDT-PRO, http://www.l-com.com
2			L-com, Inc., Antenna model #: RE11DP, http://www.l-com.com
3			Laird Technologies, Antenna model #: CP24-12, http://www.lairdtech.com
4			L-com, Inc., Antenna model #: HG2412SY, http://www.l-com.com
5			Superpass™, Antenna model #: SPDG13H22, www.superpass.com

Table 3

	Antennas				
	1	**4**	**3**	**5**	**2**
Fraction Read	0.109	0.097	0.090	0.090	0.082
Average Reads Per MAC Address	6.8	8.3	7.1	8.2	3.4
Total Traffic Volume[1]	85,936	89,280	54,645	48,189	39,374
Average Traffic Volume[2]	10,742	11,032	10,929	10,219	11,672
Hours Tested	168.25	167.25	98.0	95.25	70.25
Included Weekend?	Yes	Yes	No	Yes	No

[1] **Total vehicle count (over testing period).**
[2] **Average vehicles per day (over testing period).**

Table 4

Antenna #	1	4	3	5	2
1	0	1	1	1	1
4		0	1	1	1
3			0	0	1
5				0	1
2					0

Table 5

	5		4		1		3		2	
	8/17 - 8/20	7/27 - 7/30	8/24 - 8/27	9/10 - 9/15	7/30 - 8/3	8/27 - 8/31	8/31 - 9/3	9/7 - 9/10	8/8 - 8/10	8/20 - 8/24
Traffic Volume (TV)	40,164	40,955	39,278	65,371	49,995	48,177	53,148	40,047	24,416	48,610
Number of unique MAC addresses detected by DCU1[1]	4,046	4,506	3,423	4,899	4,420	4,496	4,872	3,462	1,963	3,619
Number of Travel Time Samples (TTS)[2]	3,837	3,916	3,898	4,987	3,839	3,693	4,125	2,847	1,398	2,781
TTS as Percentage of TV	9.55%	9.56%	9.92%	7.63%	7.68%	7.67%	7.76%	7.11%	5.73%	5.72%
Weighted Avg. % Match	9.56%		8.49%		7.67%		7.48%		5.72%	

[1] Only counts the MAC address of a Bluetooth-enabled device in a passing car <u>once</u> during the test period.

[2] Repeat occurrences of the a MAC address detected at DCU1 were accounted for if the specific MAC address was also detected at DCU2

Table 6

	2		1		3		5		4	
	8/8 - 8/10	8/20 - 8/24	7/30 - 8/3	8/27 - 8/31	8/31 - 9/3	9/7 - 9/10	8/17 - 8/20	7/27 - 7/30	8/24 - 8/27	9/10 - 9/15
Calculation Method	**First-First**	**Avg-Avg**	**Avg-Avg**	**Avg-Avg**	**Avg-Avg**	**Last-Last**	**Avg-Avg**	**Avg-Avg**	**Avg-Avg**	**Avg-Avg**
Absolute Average Error	4.02%	4.08%	3.26%	6.61%	4.38%	5.88%	6.38%	6.06%	8.05%	7.82%
Maximum	11.32%	7.94%	8.16%	13.28%	9.84%	15.29%	15.79%	16.42%	21.05%	16.45%
Minimum	0.00%	0.00%	0.00%	1.85%	0.00%	0.00%	0.00%	0.00%	1.27%	0.94%
Standard Deviation	3.25%	2.96%	2.51%	3.69%	3.53%	5.15%	5.25%	5.55%	6.74%	5.24%
Combined Absolute Avg Error	4.06%		4.91%		5.02%		6.22%		7.91%	
Average Error	0.17%	-2.86%	-1.21%	-7.08%	-3.22%	-6.02%	0.08%	-3.63%	-1.10%	-7.68%
Standard Deviation	5.38%	4.27%	4.13%	3.83%	4.95%	4.51%	8.20%	8.03%	11.67%	6.64%

Figure 1

H-field vector orientation

E-field vector orientation (polarization)

Wave propagation direction (H x E) Energy Flux (W/m²)

(a)

Ideal Isotropic Antenna Gain = 1

Directional Antenna Gain > 1

(b)
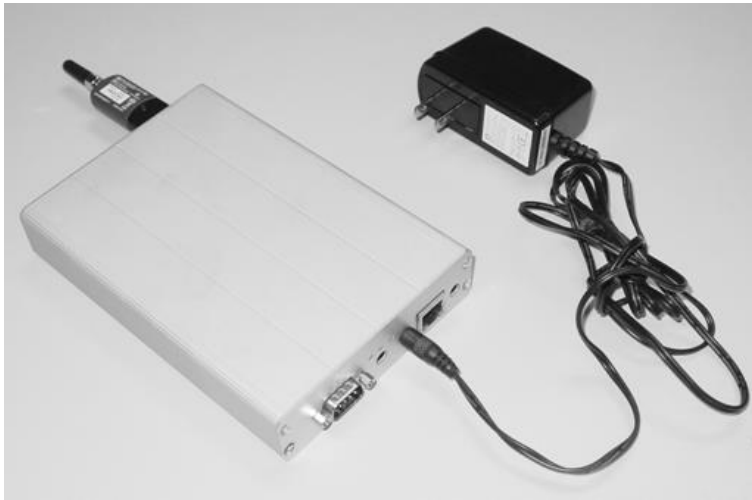
Figure 2
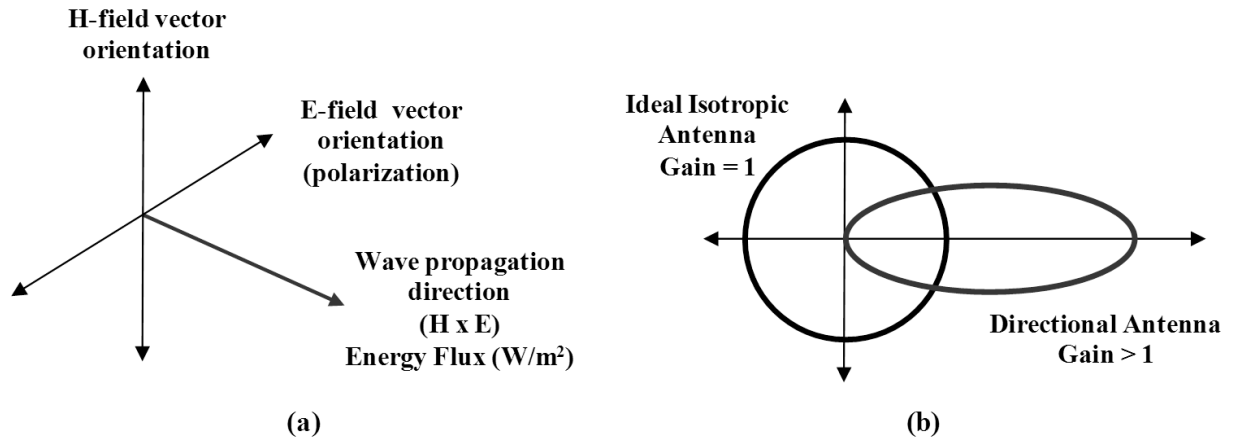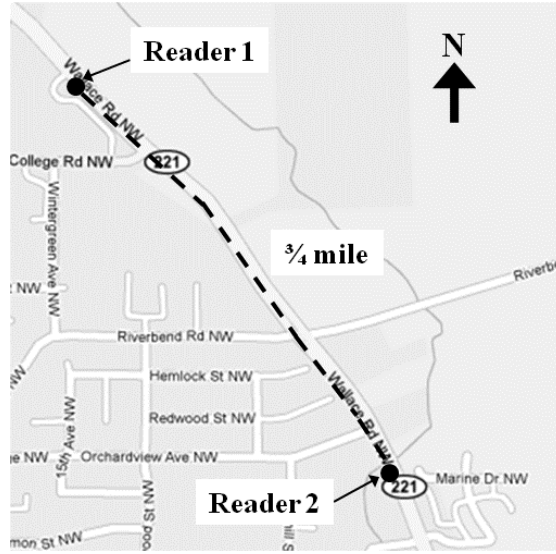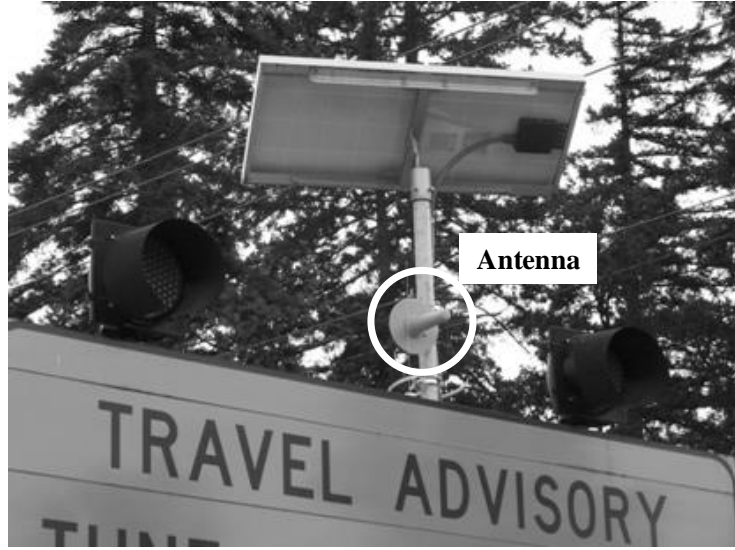
Figure 3

(a)   **(b)**

Figure 4

```
5:1A:44:9,08/03/10,11:16:32,00:01:95:0A:CC:A8
A:02:B0:F,08/03/10,11:16:32,00:01:95:0A:CC:A8
F:3A:94:F,08/03/10,11:16:36,00:01:95:0A:CC:A8
5:E7:B9:0,08/03/10,11:16:36,00:01:95:0A:CC:A8
A:02:B0:F,08/03/10,11:16:36,00:01:95:0A:CC:A8
```
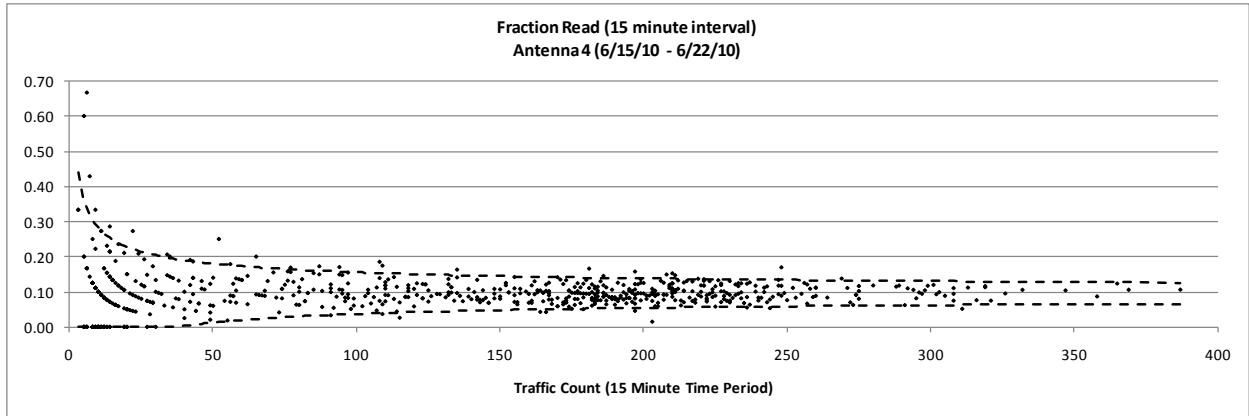
Figure 5

Fraction Read (15 minute interval)
Antenna 4 (6/15/10 - 6/22/10)

Traffic Count (15 Minute Time Period)

Figure 6

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0:0D:EC:7	9/12/2010	20:49:19	Earliest time
0:0D:EC:7	9/12/2010	20:49:24	
0:0D:EC:7	9/12/2010	20:49:33	Average group time
0:0D:EC:7	9/12/2010	20:49:37	
0:0D:EC:7	9/12/2010	20:49:42	
0:0D:EC:7	9/12/2010	20:49:47	Latest time

Group

Figure 7

Figure 8