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Empirical evaluation of Bluetooth and Wifi scanning for road transport

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Abstract

Recently there has been significant interest of researchers and practitioners on the use of Bluetooth Media Access Control Scanner (BMS) as a complementary transport data source. The concept behind BMS is rather simple. BMS scans the Media Access Control Identifier (MAC-ID) of the *discoverable* Bluetooth (BT) devices within its communication range. Most modern portable electronic devices such as mobile phones, car navigation systems, headphones, etc are equipped with BT, usage is increasing with the improved availability of the devices. Installing time-synchronised BMSs on the road network has the potential to provide live reporting of the transportation of BT devices over the road network. Assuming the devices are transported by vehicles, individual vehicle travel patterns can be easily obtained. On a similar concept, Wifi Media Access Control Scanners (WMS) which scan the MAC-ID used for Wifi communication by the devices can also be used. Currently WMS are not widely used, and their usage is still being explored. The communication difference in BT and Wifi technology; availability of live BT and Wifi in the devices; and technical differences between BMS and WMS can result in significant differences in the quality and quantity of data being collected by each device type.

This objective of this research is to empirically evaluate the BMS and WMS devices in terms of availability of the traffic data and accuracy of travel time estimation. The strengths and weakness of the two scanners (BMS and WMS) are identified. Real surveys along the arterial corridor in Brisbane are performed to empirically support the findings. The performed survey includes measurements of real flow traffic, BMS data and WMS data along Ipswich Road, Brisbane. The proportion of traffic being captured by each BMS and WMS are evaluated and the type of device being captured by BMS and WMS are also identified. The knowledge gained is helpful for researchers and practitioners to understand the current and long term insight on the use of both BMS and WMS as complementary traffic data sources.

1. Introduction

The ability to accurately calculate travel times is an important issue in the ever growing cities and their road networks. Travel time estimation has long been a topic of research and researchers have proposed numerous models for motorways, (Bajwa, et al., 2003; Chien & Kuchipudi, 2003, Bhaskar, Qu and Chung, 2013) and arterial network, (Dion & Rakha, 2006; Xia, et al., 2011, Bhaskar, et al., 2011; Bhaskar, et al., 2009). Most of these models utilise loop detector data, which is the oldest and widely used transport data source. With the advancement in technology other data sources such as BT and Wifi scanners are being explored as a complementary transport data (Bhaskar, 2013*a*, Bhaskar, 2013*b*, Bhaskar, et al.,. 2013, Bhaskar and Chung, 2013, Kieu, Bhaskar and Chung, 2012).

Transport issues affect everyday lives of each individual who inhabits these cities, from the daily commute to work during the peak periods of the day, to the number of trips taken to local attractors and areas. With the size of the cities ever expanding, the range of transport options for many residents is limited to vehicles, either privately owned or public transport. This equates to more users on the road network, increasing congestion of the current network, thus increasing travel times.

Traffic tends to be heaviest along routes that have a higher capacity. Motorways (or Freeways) have a higher capacity, but also attract a significantly larger percentage of users due to the perception of higher travel speeds. During peak periods, the travel speeds along these major pieces of infrastructure can often be as low as those of the supporting arterial road network that often run parallel. Being able to see real-time travel times may have the affect of being able to determine which route is the least congested for commuters.

Presently there is a range of traffic detection methods available for councils to obtain data, including instruments that measure volumes of vehicles, tracks specific vehicles, detects when vehicles are present. The issue with this technology is the expense in deployment over the entire road network.

The objective of this paper is to compare data sets obtained by running trials at two locations in Brisbane, along major arterial roads, and data obtained from the Brisbane City Council. The trials run obtain Wi-Fi data sets, which is to be compared with the BCC Bluetooth (BCC-BT) data obtained from the currently installed BT scanners throughout the Brisbane road network. The comparison of these data sets is carried out to determine if the current practice of scanning for BT devices only provides a more accurate data set to that of scanning for Wi-Fi devices, as they increase in popularity.

2. Bluetooth and Wi-Fi MAC Scanners

A recent addition to the technology is a BT Media Access Control Scanner or BMS. The concept behind the BMS technology is rather simple, in that the scanner unit scans discoverable Media Access Control Identifiers (MAC-ID's) of various modern digital devices, such as mobile phones, vehicle navigation systems, vehicle stereo systems. The usage of such devices has increased dramatically since the discovery of BT Technology in 1994 by Jaap Haartsen and Sven Mattisson, while working for Ericsson in Sweden. This technology has become a central part of modern day vehicles, to allow connectivity of cars stereos to personal devices, pairing of hands free headsets to mobile phones and GPS systems.

2.1 Bluetooth connection method

A BT device has two states and seven sub-states, the two states being standby and connection. In standby state, the device has no interaction with other devices, whereas in the connection state, data is able to be transferred between devices. The seven sub-states or modes of the connection are;

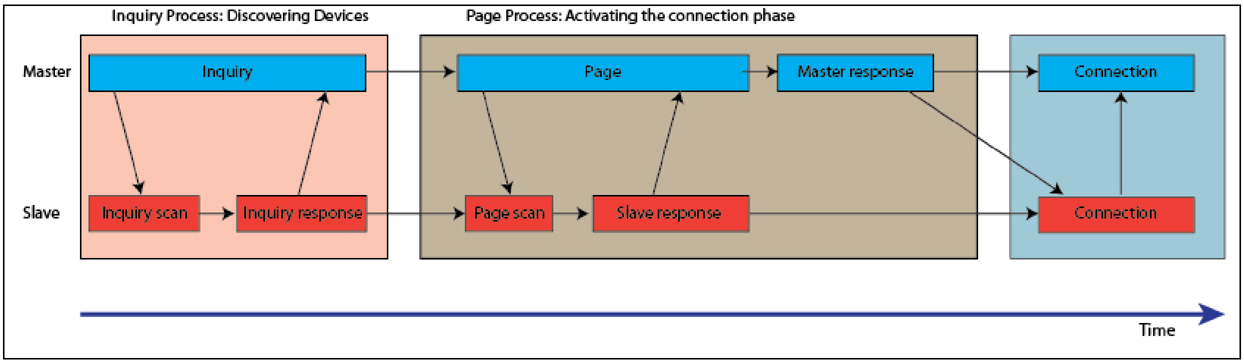
inquiry>inquiry-scan>inquiry response>page>page scan>slave response>master response.

For a connection to occur, the following must happen;

1. The master device has to be in Inquiry mode to enquire about the other devices within range;
2. If the slave device is in inquiry mode, then it scans the inquiry sent by the master device. The slave device can switch to inquiry response mode to respond;
3. The master device detects the response from the slave device within its range and may switch to Page Mode
4. The slave device has to be in page-scan mode to scan the page sent by the master and may then switch to slave-response mode to send its response.
5. The master has to be in Master-response mode to send further information to establish a final connection between the devices.

The connection of BT devices is complex but can be simply modelled as shown in Figure 1.

Figure 1: Model of how BT Devices Connect (Bhaskar, et al., nd).



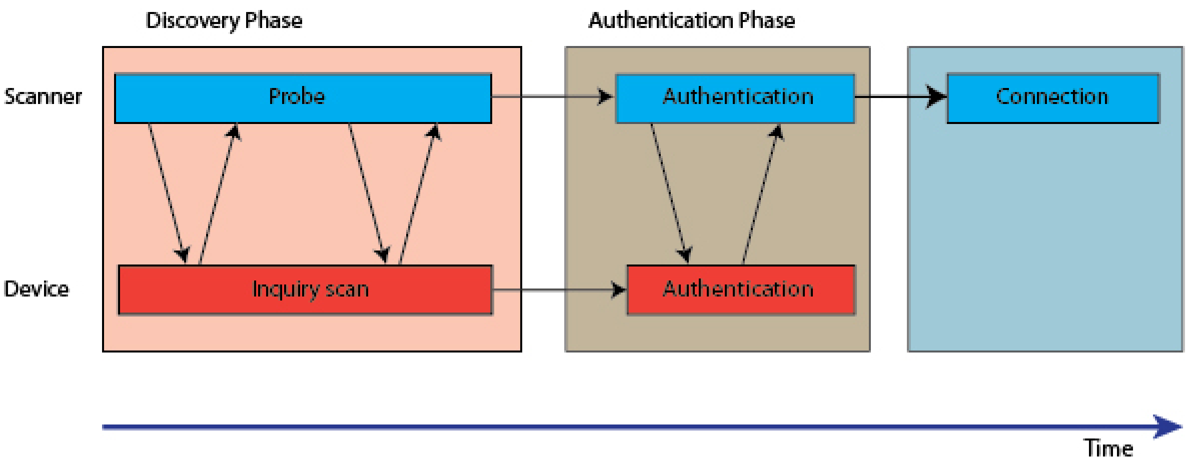
The inquiry phase of connecting BT devices may take 10.24 seconds, as the scanner has to scan 79 frequencies that are available to BT, between 2.402GHz and 2.48GHz.The frequencies of BT are separated into 32 channels, made of two 16-channel subsets called trains. Scanning of each of the trains takes 0.1 seconds and each train is scanned 256 times to provide adequate collection time from other BT devices (Vo, 2011).

2.2 Wi-Fi connection method

Wi-Fi Media Access Control Scanners, or WMS, use radio waves to transfer data from one device to another. Wi-Fi stations send out Beacon messages, at a default 100 ms cycle, to announce the presence of a network. The Beacon message includes information such as the Service Set Identifier (SSID) and capability information. Mobile phones operate in ad-hoc mode and form an Independent Basic Service Set (IBSS). Wi-Fi signals are transmitted on two channels of differing frequencies, 2.4 GHz and 5 GHz (Microsoft, 2003).

Wi-Fi interfaces also scan wireless channels to discover peers by means of two modes of scanning; *passive* and *active*. In passive scanning mode the device listens to incoming Beacon massages at regular intervals, switching between the two channels. In *passive* mode the device does not respond to the Beacon messages by means of probe requests. In *active* mode, the device actively searches for peers by broadcasting probe request messages on each possible channel, and awaits probe responses. The probe responses include information similar to the information included in the Beacon message (Han & Srinivasan, 2012). The Wi-Fi scanners used for these trials scanned in *active* mode.

Figure 2: Active mode scanning model for Wi-Fi



Compared to the BT device (recommended) inquiry time of 10.24 seconds, Wi-Fi has a total inquiry time of as little as 8ms. This allows detection of devices every second, allowing vehicles that travel through a zone to be detected at a much quicker rate.

3. Current uses in industry

BT scanners are currently being used by many cities throughout the world as a means of travel time calculation. Brisbane City Council currently has 142 BT scanners in operation along arterial roads on the Brisbane road network. These scanners detect MAC-ID's of vehicles and personal devices along the arterial roads, and collect real time data for analysis by the Brisbane City Council.

Currently there are no Wi-Fi scanners in operation in Brisbane, and the popularity of these scanners is only just starting to increase throughout the world. Wi-Fi detection is a relatively new technology, and its potential as complementary traffic data is currently being explored.

3.1 Known limitations of devices

Although the BT technology is becoming rapidly popular in the transportation industry for traffic monitoring, travel time forecasting and speed estimating, there are still unaddressed limitation of these technologies that one must take into consideration.

It is recognized that one of the biggest issues with scanning MAC addresses of BT or Wi-Fi equipped devices is that they may be captured by the scanning units more than once whilst the device is within the range of the data collection unit (Quayle, et al., 2010). Hence, Quayle et al. (2010) further suggest that first-to-first and last-to-last detection times of the devices' MAC addresses should be used to determine the travel time samples. However, this does not take into consideration the possibility of the device being scanned more frequently near one data collection unit than the other and no mention has been made with regards to the differences in the accuracy of these methods. Porter, Kim & Magana (2011) also acknowledged the same issue of multiple reads of the same MAC address whilst the commuters travel within the data collection unit's coverage area. They further claim that it is not apparent which of the multiple readings best represent the commuters' position and when they are closest to the data collection unit. Hence the importance of developing this technology is stressed by which the only MAC address that is scanned and retained by the data collection unit is the MAC address that was scanned from the shortest distance away from the unit itself (Porter et al., 2011). Nonetheless, the need for the existing devices has also been illustrated; in fact devices that are able to scan MAC addresses of BT devices more frequently can be significantly beneficial to measure intersection performance, as this allows for accurate determination of the duration for which a vehicle remained within the scanning zone (Porter, et al., 2011).

Another limitation of the BT media scanning devices was recognised by an experiment carried out by Malinovskiy, Wu, Wang and Lee (2010), which established that compared to automatic license plate recognition, travel times computed using the MAC address data is usually overestimated. Hence, it was proposed from the findings of this experiment that a faster moving vehicle has a good chance of travelling through the scanning zone without being detected (Malinovskiy et al., 2010). This suggests that if the data was to be collected over a faster moving traffic zone, there may be a significant loss of data in terms of MAC addresses that could have been captured in comparison to the slower moving traffic.

In the current market, there exist numerous forms of BT-based data collection systems for traffic monitoring; each device having different capabilities in terms of either storing the data locally or transmitting the MAC address data over a network, allowing for online retrieval of information (Malinovskiy, et al., 2010). With regards to the larger scale implementation of BT-based data collection systems, an issue that may be encountered is the storage or transmission of the data gathered by the data collection units. It is not unreasonable to assume that for permanently installed data collection units on motorways, arterial roads or signalised intersections a significant volume of MAC address data will be collected, which further requires a stable information capturing system to support the exponentially increasing set of data (Kim, et al., 2012).

4. Current alternatives to BMS and WMS

There exist several different technologies that have been previously developed allowing for automated traffic monitoring to compute travel times; providing similar results to that of BT and Wi-Fi Media Scanners. Porter et al. (2011) carried out a thorough research and established that all technologies for automated travel time data collection can be categorised into three main methods of data collection; namely indirect methods, vehicle tracking methods and vehicle re-identification methods.

The table below compares BMS and WMS with the range of different. The three main dimensions that have been compared are the accuracy of detecting and tracking specific vehicles as they move through the road network, cost of implementing the technology, and the privacy concerns that a type of technology may raise.

Table 1: Comparison between various traffic scanner technologies

Technologies	Accuracy	Cost	Privacy
BT Media Scanners	High	Low	Moderate
Wi-Fi Media Scanners	High	Low	Moderate
Loop Detectors	Low	High	Low
Magnetic Sensors	Low	Moderate	Low
License Plate Recognition Systems	High	High	Moderate
RFID	High	High	Moderate
GPS Tracking Systems	High	High	High

5. Privacy of individuals in relation to data collection

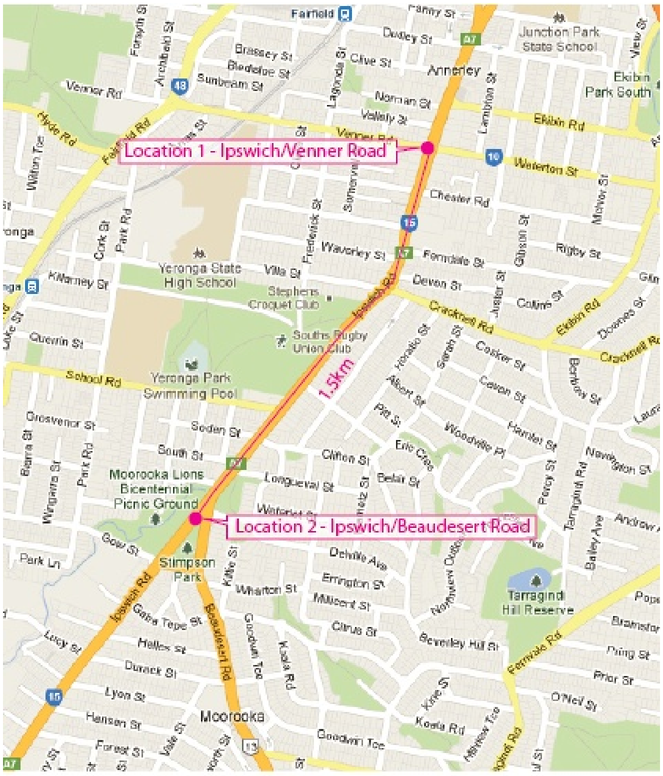
BT-based data collecting units for traffic monitoring work on the basis of re-identification. In explicit terms, the MAC address of a BT capable device is captured by data collection units multiple times and the readings are then manipulated in order to compute information regarding the commuter’s travel time, route choice, speed, etc. As the only data captured by the collection units are the MAC addresses of BT devices, there is very little privacy concern as these have no direct link to any personal or sensitive information. Moreover, the BMS and WMS can encrypt the MAC-ID’s at the device level, which can prevent the access of MAC-ID to the operators and data users.

Nevertheless, research also shows that although the MAC addresses provide little to no personal information, by having collected this data over larger BT scanning networks and longer periods of time, user behaviour and travelling habits may be derived from this data and the user can be traced (Porter et al., 2011). The report further argues that MAC addresses of BT capable devices are generally set by its manufacturers. Hence, it may be possible to track down the device product number via the MAC address captured through the company’s registration database. However, there are large possibilities that the product may not be registered, the buyer and the consumer may be different entities or the purchase transaction may not be able to reveal the identity of the buyer (Porter et al., 2011).

6. Planning of trial and installation of devices

The location selected for the trial of the devices was along a major arterial and freight route in Brisbane's south, Ipswich Road (see Figure 3). The trial was conducted on the 15th May 2013 (working Wednesday) between 8:30 am and 10:00 am. The two sites at this location were selected due to the fact that Brisbane City Council also has BT Scanners installed near both sites. The first site is located at the intersection of Ipswich and Venner Roads, with the second site being positioned at the junction of Ipswich and Beaudesert Roads, approximately 1.5 km south of the first site.

Figure 3: Location of the trial sites



6.1 Device installation

The devices are pre-assembled in their own casing, consisting of the device, an external solar panel to charge an internal battery, and aerials attached to the device. The batteries were fully charged through the solar panel for the trail to ensure that the devices had enough power to function effectively for the peak time period.

As the devices are self contained, very little is required in the way of on-site installation. The boxes are to be placed so the solar panel can continue to power the device and charge the battery, and the aerials are to be positioned to ensure that they can detect devices on the in-bound traffic lanes.

6.2 Range of the devices

The range of the devices depends largely on the range of the aerial fitted to the device. For the purpose of this experiment, two main types of aerial were used, as seen in Figure 4.

Figure 4: The two aerial types used during the trial

Aerial 1	Aerial 2

To determine the range of the aerials, the device was set up with a laptop to monitor the detected devices in real time. A controlled device, with a known MAC-ID was monitored as it moved away from the scanner. When the device was unable to be detected by the scanner, the device was deemed to be out of range. The distance between the device and the scanner was then measured using a GPS based device, determining the range of the attached aerial. This process was carried out with both aerials.
The range for aerial 1 was found to be 200 meters, while the range for aerial 2 was 150 meters. Each of these ranges should sufficiently cover a six lane roadway, which is the widest of the corridor where the experiment was carried out.

7. Data filtering and analysis

The collected data was filtered and analysed using the following process.

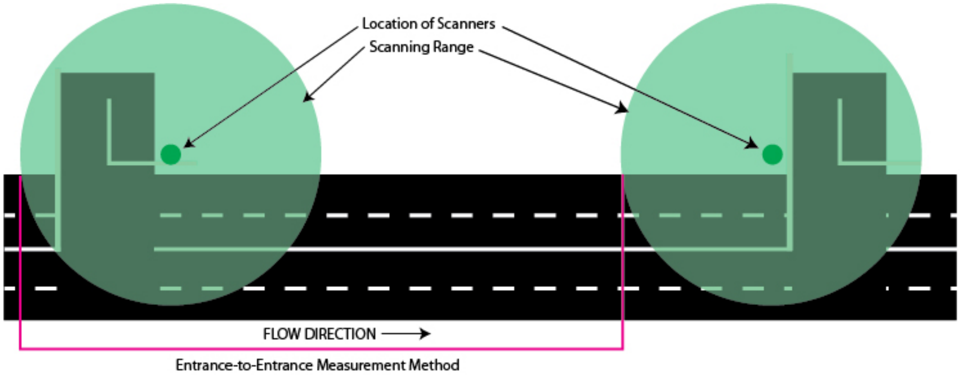
7.1 Removal of multiple devices in same set

When the data was collected from the device, it was noted that there were several instances when the same MAC-ID was collected. For analysis, these multiple appearing MAC-ID's were removed. Selecting which address to remove from the data can be done in two ways, selection of the first or last appearance of the device, that is use the timestamp associated with the first time the device appears, or the last time the device appears.

7.2 Entrance-to-Entrance

The entrance-to-entrance method involves removing the reoccurring devices after the first detection. This method will show the vehicles as they enter the range of the scanner, as seen in the image below.

Figure 5: Entrance to Entrance Diagram

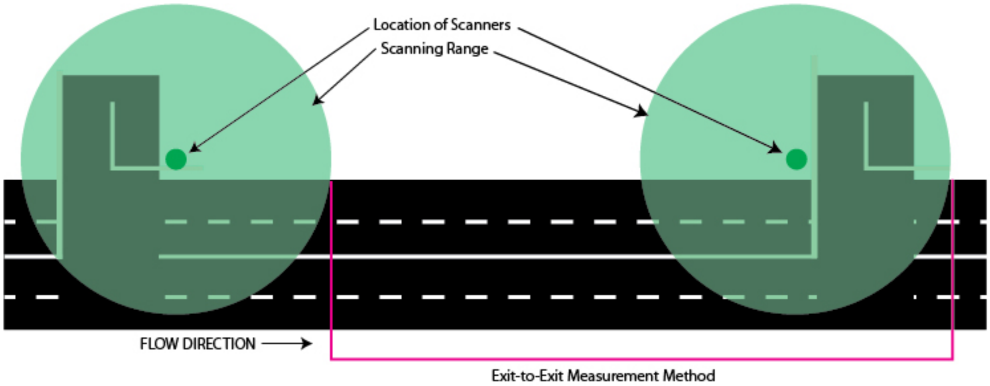


The vehicles entering the first sensor range may actually be stopped at the intersection, with dwell time for a stop signal. The amount of time that the vehicle is stationary depends on the level of congestion and the phase time of the intersection. If traffic is congested along the road after the first intersection, dwell time may increase in the range of the scanner.

7.3 Exit-to-Exit

The exit-to-exit method involves removal of all but the last occurrence of the MAC-ID from the data. This method eliminates the dwell time at the first intersection, but includes the dwell time at the second sensor.

Figure 6: Exit to Exit Diagram



Traffic engineers use either method for traffic analysis. However for the purpose of this analysis, exit to exit method is used. In the process of filtering out multiple MAC-IDs from the original data set, only the last occurring instance of the MAC-ID was used in the analysis.

7.4 Filtering of data

The data gathered required filtering for various purposes, one of which is the removal of detections that are not vehicles. This is done by application of a time limit in which the device can be detected for. If a device is detected for the whole time of the trial, it was removed as it is not likely to be a vehicle, instead more likely to be a network associated with a building. The time limit applied to the device was 5 minutes. If the device was still in range after this time period, the device was removed from the data. Even though the location of the scanners was near intersections, the amount of stopped time vehicles incur at red traffic signals should be less than the 5 minute time limit. If a device is detected multiple times over the course of the trial, but not conjointly within a 5 minute period, it is considered as multiple trips and counted towards the unique data totals.

Filtering the data was done using Microsoft Excel. The raw data from the trial had a timestamp that was in Epoch time, the number of seconds since January 1, 1970. This time stamp was converted to local time by using the following formula.

Equation 1: Epoch Time Converter Formula for Excel

$$= (((\mathrm{TIMESTAMP} - (6 * 3600))/86400) + 25569)$$

The timestamp was also in Colorado local time, so to convert to local time, 16 hours was added to the resultant time.

Pivot tables were used to filter the multiple MAC-ID's, with the pivot table only displaying the individual MAC-ID's. The pivot table was also used to determine the maximum value of the timestamp, effectively meaning the last time the device was in range of the scanner, or its end time.

The pivot tables were created for both the upstream and downstream data sets, and the highlight multiples function was used, to show any matching MAC-ID address occurring both up and down stream. Filtering of the data also requires matching the MAC-ID of each device in two forms, from up-stream to down-stream, and in the reverse order, down-stream to up-stream. Filtering the data this way allows the direction of traffic flow and travel times to be determined.

The sort function was then applied to sort by highlighted cells, allowing all matching data to be counted quickly, to give the total number of matches to the set. The matches were then checked against the raw data to determine the length of time the device was in the range of the scanner. Any device detected in the range of the scanner for longer than 5 minutes was removed.

The data was also analysed using MATLAB, using similar processes and the two data sets were compared.

7.5 Difference in volumes of BMS and WMS devices

There was a significant amount of variance observed between the amount of matching Wi-Fi and BCC BT detections. The table below shows the filtered data from the trial, with the total number of Unique MAC-IDs detected from each site of the trial, up and down stream. It also shows the total number of matching MAC-IDs from the trial, that is MAC-IDs that appear both at up and down stream, providing route information and travel time analysis data.

Table 2: Number of Unique MAC-ID detections and matching MAC-IDs at each location

	Unique MAC-IDs		Matching MAC-IDs
	Up	Down	
BCC BT	1505	1433	1191
Wi-Fi	1079	495	149

7.6 Percentage of useable data

The percentage of useable data shows the relationship between the amount of matching detections and the number of unique MAC-IDs scanned. This is useful to determine the amount of effectiveness of the data collected from each scanner. The equation used for determining the percentage of useable data is the ratio of matching MAC-IDs from both upstream and downstream locations and the total number of observed unique MAC-IDs from both streams.

Equation 2: % of Useable Data Equation

$$\%\ Useable\ Data = \frac{Matching\ IDs\ Upstream + Matching\ IDs\ Downstream}{(Observed\ Unique\ IDs\ Upstream + Observed\ Unique\ IDs\ Downstream)}$$

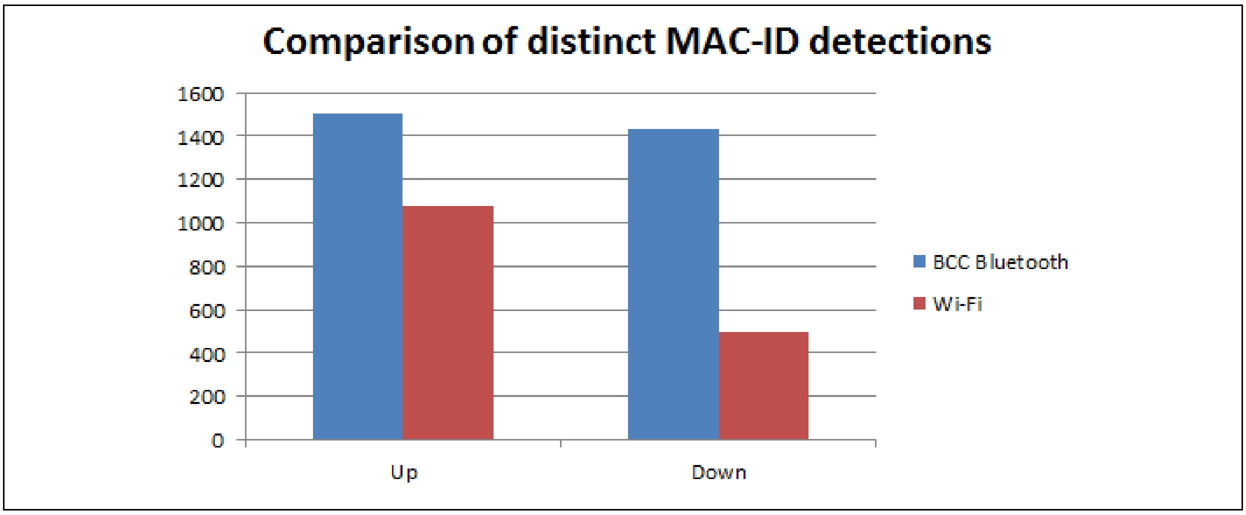
The percentage of useable data from the trial is shown in the table below.

Table 3: Percentage of Useable Data

% of Useable Data	
BCC - BT	81%
Wi-Fi	19%

Table 4 above shows that there is a significantly higher rate of % useable data from the BCC BT scanners compared to the Wi-Fi scanners. It is important to note that these figures have been somewhat skewed by the lack of unique detections at the downstream locations of the trial for Wi-Fi (495 downstream - 1079 upstream). Had there been more unique detections downstream at this site, the number of matching MAC-IDs may have been higher, changing the outcome of the % Useable Data.

Figure 7: Comparison of distinct MAC-IDs detected via WMS and BCC BT Scanners

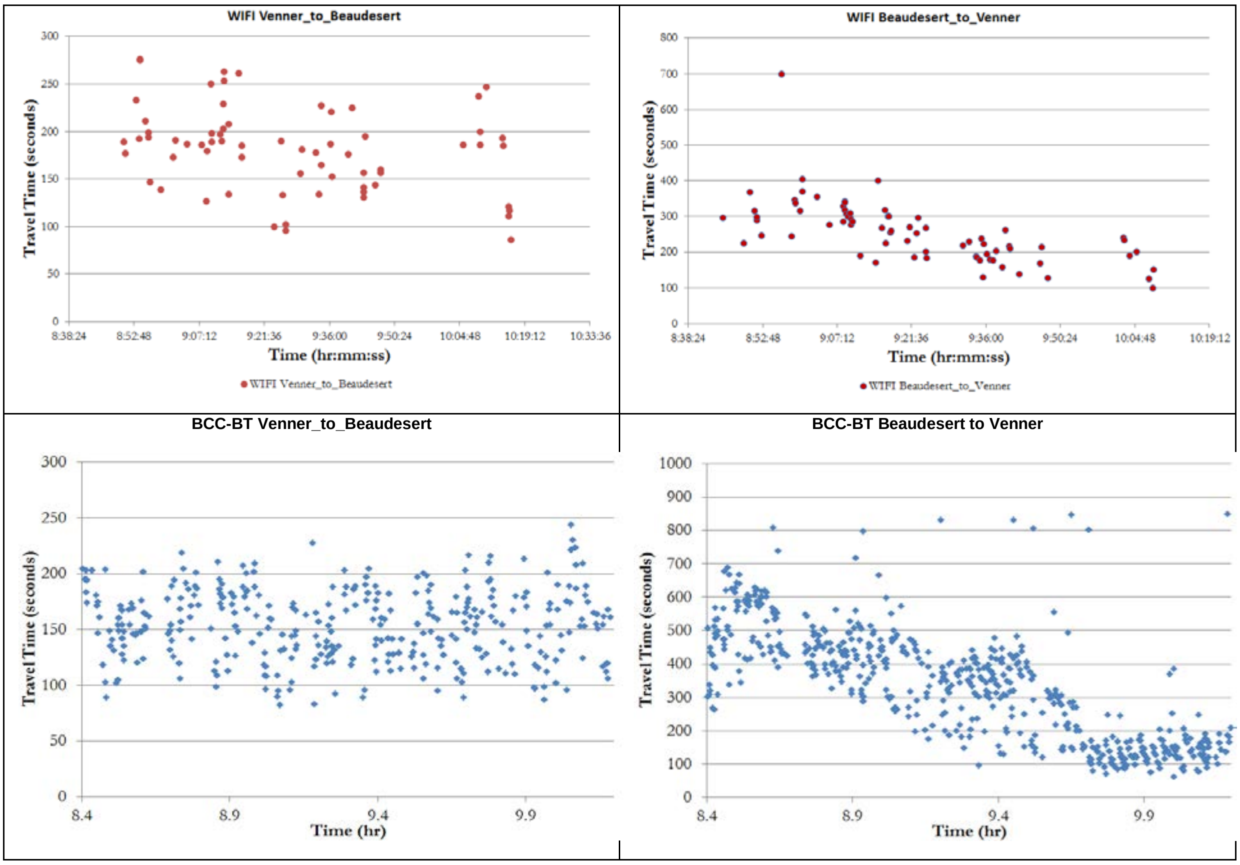


The figure above compares the number of distinct MAC-IDs detected using the experimental set-up and BCC BT data. Although the same devices were used at both locations, it is seen that the number of unique detections near the Beaudesert Road site are comparable to the BCC BT data set; however the Venner Road site captured significantly lower number of unique MAC-IDs compared to the BCC BT data set. A possible reason for this is the location of the scanner and its surroundings. At the Venner Road site, the location of the scanner device used was not the same location as the BCC BT device as there was no suitable place to set up the device.

While the aerial used should have enough range to capture vehicles through the intersection, the better location of the BCC BT scanner will allow that device to capture unique devices travelling not only along Ipswich Road, but also along Venner Road, a busy sub arterial road. By capturing devices that are also travelling along Venner Road, the total number of unique devices will be significantly larger. Furthermore, the Wi-Fi scanning device may have suffered due to the number of other Wi-Fi signals in the area. The scanning interval of device may have lead to a number of devices being scanned multiple times, while unique devices were not captured, due to the speed in which they passed the scanner. The average scanning interval for the device is a 2 second cycle; however the device is only capable of detecting 5 devices every scanning cycle. Due to the amount of stagnant Wi-Fi signals in the area, the number of total unique detections, and the limits of the scanner, the total number of unique detections may be lower than those of a scanner that is used in an area with less permanent Wi-Fi signals.

8. Travel times

Figure 8: Travel times of Wi-Fi and BT devices from trial



The above graphs illustrate the variation in travel times in both inbound and outbound directions. The top graphs represent the travel times determined using WMS and the bottom graphs represent the travel times determined using the BCC-BT data.

Overall, it is seen that traffic from Beaudesert Road to Venner Road illustrates a negative trend showing decreasing travel times; a result of dissipating morning peak hour traffic. The traffic from Venner Road to Beaudesert Road however shows no correlation over the experiment duration and illustrates a varying range of different travel times signifying free flowing traffic. The travel time in both directions ranges from 50 seconds to almost 700 seconds according to the graphs above. Although there were 5 signalized intersections between the two data collection units, it was observed that majority of the traffic on this arterial road was given priority by means of green signals, allowing for traffic times to be as low as 60 seconds. With the larger travel times, it is safe to assume that intersections may have interfered with their journey. The major outliers indicating travel times near or greater than 700 seconds may indicate cyclists or pedestrians and are safe to ignore in this instance.

Comparing the number of matching MAC-IDs, it was observed that only 149 matches were captured with the WMS while the BCC BT scanner captured 1191 matching MAC-IDs. It can be argued that a portion of the lack of matching MAC-IDs can be due to the limited unique detections observed at the Venner Road site for reasons as explained in the previous section. Furthermore, this gap may also emphasise the difference in the devices utilised by BCC and the devices used for the purpose of this experiment. Over this particular experiment, it was found that there is a higher penetration rate of BT in vehicles when compared to Wi-Fi, however further research is needed to confirm or reject this hypothesis.

9. Conclusion

Both BMS and WMS share similar concept of capturing the unique MAC ID's of the BT and Wifi devices, respectively. Though the protocol for BT and Wifi are technically different, due to which Wifi can have almost instantaneous scan, whereas BT required around 5-10 seconds for scanning. One might expect more Wifi samples than BT on the road network. However, our initial experiments from real site indicate that there are more BT than Wifi observations. This can be contributed to the higher availability of BT in cars.

Commercially available BMS and WMS have capacity of maximum number of scans per cycle. For instance, BCC- BMS scanners has capacity of 15 MAC-ID/scan. If the scan cycle is 20 seconds, then maximum number of BT devices that can be captured in 20 seconds is 15. WMS we have used has capacity of 5 ID's per cycle. Wifi scan cycle used is 2 seconds. If BMS or WMS are placed close to areas where significant amount of Wifi signals are present then it can significantly impact the performance of WMS in terms of percentage of usable data. For instance, shopping centre or residential areas can have continuous Wifi signals available. However, there will be limited affect on BMS, as in-build car BT is off once the car is turned off.

In this paper, only limited measurements of WMS are performed, and it is recommended to perform more measurements on different sites to back the findings of this paper.

The scanning cycle of the Wi-Fi scanner is every two seconds; however in those two seconds, the scanner was only able to detect a maximum of 5 Wi-Fi devices. If the scanner is positioned in a location where there is a significant amount of Wi-Fi signals, such as near businesses or shopping centres, the total number of unique detections will be affected. For best results, the scanner should be used in locations where the interference of surrounding areas Wi-Fi signals will be minimal. The Venner Road trial may have been affected by the number of businesses in the area and it is not unreasonable to assume, each with their own Wi-Fi signal.

A possible solution for this would be to use aerials with adjustable ranges or directional aerials, to ensure that unnecessary interference from surrounding signals is not encountered.

Studying the travel time data for Wi-Fi against the BCC-BT, it shows that BT was able to recognise a significantly higher number of MAC-ID matches at one of the two locations within the same duration when compared to the MAC-ID matches that were obtained using WMS. Although this seems to strengthen the argument that BT technology implemented by BCC is much superior. As the BMS devices have been implemented by the BCC on a large scale at approximately 145 different locations across the Brisbane region, it is reasonable to assume that best quality equipment was used. Due to the lack of availability of equipment for the purpose of this experiment, such limitations may seem to outweigh the benefits of using Wi-Fi. However, using a higher quality directional aerial may have resulted in considerably higher amounts of data matches. Although there are currently no Wi-Fi scanners installed, the analysis suggests that a combination of data should enhance the sample size of the travel time data points. Currently from BMS, on average we observe around 1-3 travel time points per minute, which is not large enough for a statistically significant average travel time estimation, especially on urban arterials where there is significant variability of individual vehicle travel time.

Integrating the data from both WMS and BMS should enhance the sample size and provide more confidence in average travel time estimation.

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