Position Determination in CDMA Networks using Pilot Beacons

by

Gokul Rameshkrishnaa

Bachelor of Technology, VIT University (India), 2008

A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirement for the degree of

Master of Science

Interdisciplinary Telecommunications Program

2010

This thesis entitled:

Position Determination in CDMA Networks using Pilot Beacons

written by Gokul Rameshkrishnaa

has been approved for the Interdisciplinary Telecommunications Program

Kenneth Baker

Timothy X. Brown

Thomas Schwengler

Date

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

Rameshkrishnaa, Gokul (M.S., Telecommunications)
Position Determination in CDMA Networks using Pilot Beacons
Thesis directed by Scholar in Residence Dr. Kenneth Baker

The FCC E-911 mandate places strict requirements on the accuracy and precision of mobile telephone user positioning. When in the open, with a clear view of the sky, these requirements are met satisfactorily by using a combination of ranging measurements to the Global Positioning System (GPS) satellites. GPS measurements are generally not available when in a tunnel or inside a building. In these conditions, the network and mobile rely solely on ranging to base stations in the neighborhood of the mobile device. Accuracies suffer when insufficient base station measurements are available to the mobile.

Currently, there is no viable solution to the problem of poor indoor positioning performance. Alternatives include Wi-Fi RF fingerprinting. This solution is applicable exclusively to indoor positioning and would require standardization before it can be deployed for E-911. Wi-Fi fingerprinting is an expensive and time consuming process. This leads to the question of whether further improvements can be extracted from the current technology?

This research investigates an alternative solution for CDMA networks that is compliant with existing standards and is relatively simpler to deploy since it does not require an upgrade of the user's mobile handset capabilities. Experiments were conducted to determine the efficacy of using pilot beacons to improve the positioning of mobile users within indoor environments. The test bed and the theory of pilot beacons for aiding position determination of CDMA cellular users is described. The results of the testing indicate that pilot beacons can improve the accuracy of positioning cellular terminals in an indoor environment.

To my parents for their constant encouragement and support

Acknowledgements

I acknowledge the guidance and the technical expertise of Dr. Kenneth R. Baker as a major contributor in the successful completion of this thesis. I have learnt a lot under his guidance, and I see this thesis as merely the first step in a hopefully long and fruitful professional association. I thank Dr. Baker for being the thesis chair.

Strong ties to the industry has been a hallmark of the Interdisciplinary Telecommunications Program and following this ITP tradition, my thesis was motivated at helping solve an important problem in the wireless telecommunications industry today. I thank Verizon Wireless and specifically Philip Ziegler for providing me this opportunity. I would also like to thank Bruce Wilson from Qualcomm for helping me understand various concepts of positioning in CDMA networks and his inputs while analyzing the vast data collected through the testing effort.

Last but not the least, I am appreciative of the technical expertise and comments of the thesis Committee members; Dr. Brown and Dr. Schwengler, in their review during the thesis defense.

CONTENTS

CHAPTER

1	Introduction			1
2	Background			4
	2.1	Prior Work		4
	2.2	Theory		6
		2.2.1	Network Architecture	6
		2.2.2	Network Based vs. Handset Based Positioning	8
		2.2.3	Control and User Plane	9
		2.2.4	Positioning Algorithms	9
		2.2.5	Pilot Beacons	11
		2.2.6	Method of Testing and Analysis	13
3	Indoor Locations with Outdoor Beacons - 1			16
	3.1	Introduction		16
	3.2	Setup		16
	3.3	Tests Performed		21
	3.4	Results		23
		3.4.1	Test with one pilot	23
		3.4.2	Test with two pilots	25
		3.4.3	Tests with three or more pilots	26

4	Indoor Locations with Outdoor Beacons -2			30
	4.1	Introduction		30
	4.2	Setup		30
	4.3	Tests Performed		30
	4.4	Results		32
		4.4.1	Only one Beacon ON with a MAR value of 50	32
		4.4.2	Only one Beacon ON with a MAR value of 50 vs. a MAR value of 1000	32
		4.4.3	Two Beacons ON, one with a MAR value of 1000 and other with a MAR value of 50	33
		4.4.4	Two Beacons ON, both with a MAR value of 1000 or a MAR value of 50	34
5	Tunnel Environment			37
	5.1	Introduction		37
	5.2	Setup		38
	5.3	Tests Performed		41
	5.4	Results - Tunnel Served By a Dedicated Sector		43
		5.4.1	T1, T2, T3	43
		5.4.2	T1 and T4	47
		5.4.3	T4 and T5	50
		5.4.4	T4 and T6	52
	5.5	Results – Tunnel Served By an External Sector		55
		5.5.1	T7, T8, T9	56
		5.5.2	T7a, T7b and T9a	57
			5.5.2.1 T7a	57
			5.5.2.2 T7b	59
			5.5.2.3 T9a	60
	5.6	Extended Tunnel Tests		61

5.7 Extended Test Results 62

5.7.1 TE1, TE1a and TE1b 62

6 Arena Environment using Indoor Beacons 66

6.1 Introduction 66

6.2 Arena Set-Up and Configuration 67

6.3 Arena Tests 71

6.4 Arena Test Results 72

6.4.1 T1, T2 72

6.4.2 T3, T4 74

6.4.3 T5, T6 76

6.4.4 T7, T8, T9 77

7 Comparison of User Plane to Control Plane 79

7.1 Introduction 79

7.2 Set-Up and Configuration 80

7.3 Tests Performed 81

7.4 Test Results 82

8 Conclusion 84

9 Future Work 88

10 Appendix 90

Bibliography 92

TABLES

Table 1: Base station parameters in the BSA	7
Table 2: LBS Rover Settings for Collecting User Plane Data	15
Table 3: LBS Rover Settings for Collecting Control Plane Data	15
Table 4: Pilot Beacon Configuration for outdoor deployment	19
Table 5: Indoor Tests, Set 1	21
Table 6: Indoor Tests, Set 2	22
Table 7: Combined results from the three test locations (meters)	27
Table 8: Combined results from the three test locations (meters)	27
Table 9: 67th and 95th percentile errors (meters) in comparison to the FCC mandate	28
Table 10: Indoor Tests, Set 3	31
Table 11: HEPE variation over different MAR value combinations for ECOT and SLHS	36
Table 12: Beacon configuration	39
Table 13: Tunnel tests	42
Table 14: Extended tunnel tests	62
Table 15: Beacon configuration for arena tests	70
Table 16: Arena Tests	72
Table 17: Control Plane vs. User Plane Tests	82
Table 18: Control Plane vs. user Plane Results: Average Error (Meters)	83
Table 19: Average Error and Standard Deviation for each beacon configuration tested in Indoor Tests, Set 1 and 2	90
Table 20: Beacon combinations in decreasing order of average overall error	91

FIGURES

Fig. 1: CDMA Network Reference Model for positioning (inside the box) along with Pilot Beacons	6
Fig. 2: PBU locations relative to existing Verizon sectors	18
Fig. 3: Weather proofing for outdoor PBU	19
Fig. 4: Test Locations	20
Fig. 5: Possible errors in a MCS solution	24
Fig. 6: Fix distribution for MCS solution using only Whizzer	25
Fig. 7: Fix distribution for MM solution using Whizzer and one of the four beacons	26
Fig. 8: CDF plot of error in meters for a given number of pilots measured by the MS	28
Fig. 9: Error distribution by fix type	29
Fig. 10: Fix distribution for ECOT with a MAR value of 50 while SLHS is OFF	32
Fig. 11: a. Fix distribution for SLHS with a MAR value of 50 while ECOT is OFF, b. Fix distribution for SLHS with a MAR value of 1000 while ECOT is OFF	33
Fig. 12: a. Fix distribution for SLHS with a MAR value of 50 and ECOT with a MAR value of 1000, b. Fix distribution for SLHS with a MAR value of 1000 and ECOT with a MAR value of 50	34
Fig. 13: Fix distribution for both beacons with a MAR value of 50 or a MAR value of 1000	36
Fig. 14: Equipment configuration and test locations for tunnel tests	39
Fig. 15: Test locations modeled relative to the actual tunnel location in yellow	41
Fig. 16: Phone x1396 Fix Distribution for Tests T1, T2 and T3	44
Fig. 17: Phone x4597 Fix Distribution for Tests T1, T2 and T3	45
Fig. 18: Phone x0428 Fix Distribution for Tests T1, T2 and T3	46
Fig. 19: Phone x0428 and Phone x1396 Fix Distribution for Tests T1 and T4	48
Fig. 20: Phone x4597 Fix Distribution for Tests T1 and T4	49

Fig. 21: Phone x1396 and x4597 Fix Distribution for Tests T4 and T5	51
Fig. 22: Phone x0428 Fix Distribution for Tests T4 and T5	52
Fig. 23: Phone x1396 and x4597 Fix Distribution for Tests T4 and T6	54
Fig. 24: Phone x0428 Fix Distribution for Tests T4 and T6	55
Fig. 25: All Phones: Fix Distribution for Tests T7, T8 and T9	57
Fig. 26: Phone x4597 Fix Distribution for Tests T1 and T7a	59
Fig. 27: All Phones: Fix Distribution for Tests T7b	60
Fig. 28: All Phones: Fix Distribution for Tests T9a	61
Fig. 29: Equipment configuration for Extended Tunnel Tests	61
Fig. 30: Phone x1396 and x4597 Fix Distribution for tests TE1, TE1a and TE1b	63
Fig. 31: Phone x0428 Fix Distribution for tests TE1, TE1a and TE1b	64
Fig. 32: Arena location showing distance from Whizzer	68
Fig. 33: Arena Configuration Showing Truth Positions (TP) and Antenna Locations (B)	69
Fig. 34: Equipment Configuration showing delays in the system for Arena testing	70
Fig. 35: Fix distribution for T1, T2 for phones at TP1, TP2 and TP3	74
Fig. 36: Fix distribution for T3 for phones at: a. TP1, b. TP2, and c. TP3	75
Fig. 37: Fix distribution for T4 for phones at: a. TP1, b. TP2, and c. TP3	76
Fig. 38: a. Fix distribution for T5, b. Fix results for T6	77
Fig. 39: All phones, Fix distribution for T7	78
Fig. 40: Pilot beacons (B), Verizon BTS (V) and test locations	81
Fig. 41: Figure illustrating the impact of geometry on ranging	85

CHAPTER 1

Introduction

There is a renewed interest in mobile cellular telephone positioning due to the huge opportunity presented by Location Based Services (LBS). A Location Based Service helps make data more accessible and improves relevance by biasing results based on the geographical location where the request originates. Wireless carriers are uniquely positioned to enable the determination of user location and may take advantage of this opportunity to develop a business [19].

More importantly, the FCC recognized very early that when a wireless device is used to request help through 911 or similar services it is quite possible that the caller may be unfamiliar with their location. This can be a problem in mobilizing timely assistance. Therefore, the FCC mandate on Enhanced 911 (E-911) services placed a strict requirement on the availability of accurate and precise position of the caller requesting emergency assistance [1]. In their current implementations, both popular 2G communication standards GSM and CDMA (IS-95) and their 3G evolutions UMTS and CDMA-2000 facilitate the acquisition of position data. For CDMA networks, the IS-801 standard describes the signaling required for position determination. The 3GPP2 version of this standard is referenced here [2].

Assisted GPS (AGPS) was invented by SnapTrack for meeting the E-911 accuracy requirements on CDMA networks [20]. The system consists of a GPS receiver in the MS that is supplemented by GPS acquisition information from the network resulting in improved acquisition, times, sensitivity, and accuracy. This system, when in the open, with a clear view of the sky, meets the requirements mandated by the FCC satisfactorily. GPS measurements are generally not available when in a tunnel or inside a building. In such cases, the MS uses a complimentary technology called Advanced Forward Link

Trilateration (AFLT) where the network and Mobile Station (MS) rely solely on ranging to base stations in the neighborhood of the MS [19]. It is achieved by measuring all the CDMA pilot phase offsets (sectors) that can be heard from MS's current location. This is essentially a specialized case of the normal pilot (PN) phase measurement that the CDMA MS performs routinely for the purpose of soft handoff.

The challenge is to ensure that at least three ranging measurements to neighboring base stations are available to provide an AFLT solution whenever necessary. The accuracy of an AFLT solution improves with the availability of additional base stations. But, the addition of base stations to the network and shrinking cell sizes are a function of the traffic capacity requirements. It may not be possible to ensure that three or more base stations are available for generating an AFLT solution everywhere.

This has led to the research and development of alternate indoor positioning technologies that replace cellular signals with other signals such as Wi-Fi, Bluetooth, as explained in the next chapter. In general, these techniques are far more accurate than what is achieved by the cellular networks now or even what is mandated by the FCC ruling. Some of these techniques provide impressive accuracies of fewer than 5 meters. Despite the availability of published research showing evidence of the same, as early as 2006 [3], these techniques have not found market acceptance. To be viable, these technologies need to go through a standardization process that produces a reference implementation for the industry to adopt. The biggest obstacle to such standardization is the need to integrate the new technologies into the MS. In the future, techniques based on Wi-Fi may be an exception to this rule if the trend of smartphones integrating Wi-Fi chipsets continues. Having said that, not all phones have Wi-Fi and therefore even radiolocation techniques using Wi-Fi may not help meet the E-911 requirements in the near future.

In the work described here, an alternative approach to solving the problem of poor indoor accuracy has been investigated for CDMA networks. This thesis investigates whether the addition of redundant ranging sources using specialized beacon devices (Pilot Beacons) can be used to improve positioning indoors where signals from neighboring sectors may be attenuated. Pilot beacon performance in three real-world deployment scenarios was tested. The campus environment consisting of multiple buildings was the first scenario tested. Next, a linear configuration resembling a vehicular tunnel was tested. Finally, a large arena environment with dedicated beacons serving them was tested.

Using the data gathered in the various tests, this work is targeted at the following main questions:

1. Does the addition of pilot beacons improve indoor positioning performance?
2. What is the improvement in performance, if additional beacons are added to the minimum number required to compute an AFLT solution?

Experiments were conducted to determine the efficacy of using pilot beacons to improve the positioning of mobile users within indoor environments. A test bed was developed at the University of Colorado – Boulder for the purpose of conducting the necessary tests. Results of the testing presented here indicate that pilot beacons can improve the accuracy of positioning cellular terminals in an indoor environment.

CHAPTER 2

Background

This chapter is divided into two sections. The first section discusses prior work relevant to the research presented here. The next section provides background theory about the architecture of a CDMA based positioning infrastructure and pilot beacons.

2.1 Prior Work

The literature on radiolocation is chiefly simulation-based since it is difficult to perform tests on a commercial live cellular network using licensed spectrum without the explicit approval of the spectrum owner. There is abundant literature that discusses radiolocation techniques and develops mathematical models that form the basis for their simulations. The mathematical model for a radiolocation system that utilizes the time of arrival of signals at the receiver was presented as early as 1991 [4]. In that work, the authors demonstrate that this approach could be extended to cellular systems. Caffrey and Stuber discuss various radiolocation algorithms such as Time of Arrival (ToA), Time Difference of Arrival (TDoA) and Angle of Arrival (AoA) based positioning in [5]. They also present reasons why AoA is more cumbersome.

TDoA is the focus of [6, 7]. A statistical point of view is adopted in [7] and comparison of various algorithms for solving a TDoA based system of equations such as root mean square error (RMSE), Gauss-Newton method, is made. The accuracies achievable from an RF propagation perspective in urban and micro cellular environments is examined in [6]. They also present data to support the claim that TDoA based schemes have accuracies of 50 - 100 meters and can satisfy the E-911 requirements. The AFLT scheme for CDMA networks is an implementation of a TDoA/ToA scheme. In practice, even with AFLT as a complementary technique to AGPS, carriers have not been able to achieve the accuracies that the FCC requires. TDoA (AFLT) requires at least three base stations for producing a position fix and the accuracy improves with additional measurements [8]. As previously mentioned, the addition of base stations to the network and shrinking cell sizes are a function of the traffic capacity requirement and it may not be possible to ensure that three or more base stations are available for generating an AFLT solution everywhere. Therefore, there is room for improvement in positioning accuracies using AFLT. The work presented here tries to extract these accuracies by introducing additional ranging sources in the cellular network.

The positioning of devices has been approached in many ways. In [9], the author provides a performance comparison of various indoor positioning algorithms. The different solutions proposed use a variety of signals like Bluetooth and Wi-Fi and sensors like gyroscopes, barometers, and inertial sensors. While dedicated indoor systems perform better than GPS, the main shortcoming of these techniques is that despite being highly accurate, they are hard to integrate into the MS. These techniques cannot be made economically viable unless formal standardization occurs.

In [10], the authors install devices called pseudolites throughout the building that act like GPS satellites and provide accurate time reference signals that can be used for trilateration. The pseudolite system is able to position users to within a centimeter or two of error. However, it is impractical to add such sensors to all indoor locations.

RF fingerprinting is suggested by multiple authors due to the limited ground that needs to be covered inside a building. Wi-Fi is the signal of choice in these works since the use of 802.11 WLAN is becoming prolific, [9, 11]. Popular test environments for positioning like university campuses and office buildings were among the first to adopt Wi-Fi. The authors were able to obtain accuracies of about 2 meters consistently using the approaches detailed in [9, 11]. If Wi-Fi could be integrated into cellular positioning standards it could be effective even for location-intensive applications like turn by turn navigation.

Academic research thus far has focused on achieving positioning accuracy through the use of newer algorithms and by adding additional sensors to supplement RF signals. The work discussed here takes an alternative approach by focusing on the problem of low accuracies resulting from the unavailability of ranging sources to compute an AFLT solution. The idea is based on the assertion that the way cell sites are planned and deployed is not optimized for positioning. A way to augment the cellular network is proposed through the use of pilot beacons.

2.2 Theory

2.2.1 Network Architecture

The CDMA network reference model as defined in ANSI/J-STD-036 [22] for E-911 positioning along with the proposed pilot beacon enhancement is shown in Fig. 1. There are a multitude of choices available to the carrier commercially for the implementation of a positioning service that is compliant with this model. The major components of the model are discussed below.

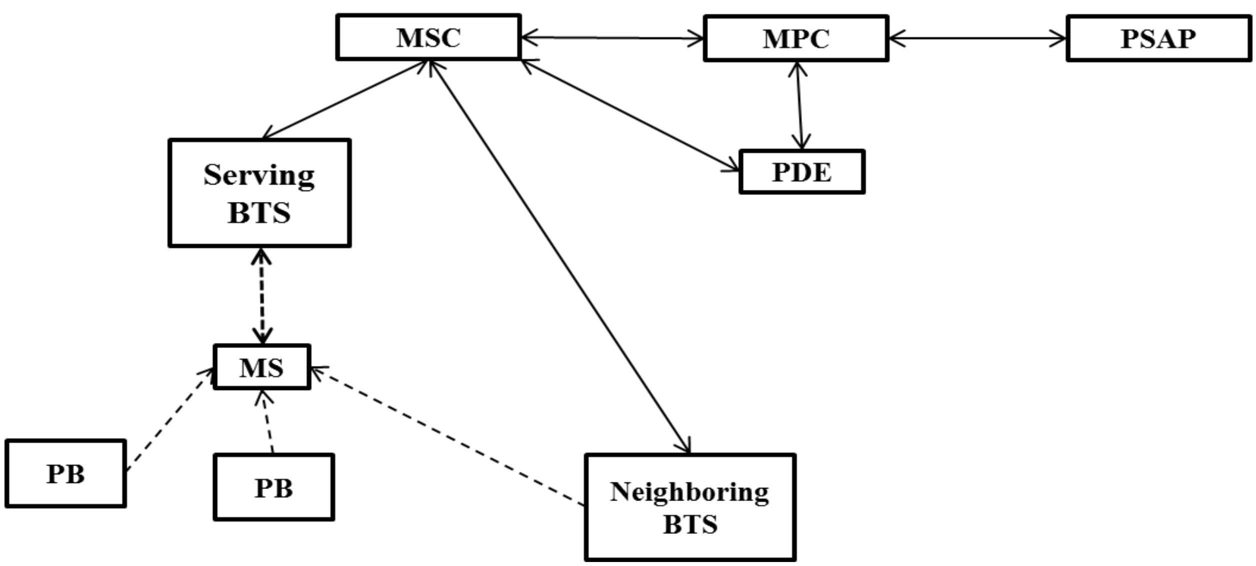

Fig. 1: CDMA Network Reference Model for positioning (inside the box) along with Pilot Beacons

The communication network consists of the Mobile Switching Center (MSC), interfaced to the Base Transceiver Station (BTS) through the Base Station Controller (BSC, not shown in the figure). These components serve to route calls from the MS to the appropriate destination. The positioning infrastructure consists of the Mobile Positioning Center (MPC), and the Position Determination Entity (PDE). The PDE is the position server that is responsible for the computation of the MS's position or facilitation of this process such that the position can be determined locally on the MS. This distinction will be clarified later in this section. The PDE supports multiple position technologies such as AFLT and AGPS. The MPC is the interface that connects the communication network to the positioning infrastructure. If multiple PDE serve the region served by a single MPC, it routes position requests to the correct PDE. During a 911 call, after the MSC sets up the call to the correct Public Safety Answering Point (PSAP), the MPC interacts with the PSAP and provides it the best estimate of the position of the MS. PSAP is the call center that is responsible for dispatching assistance to the caller.

The Base Station Almanac is a database that resides in the PDE. Each BSA contains information about a collection of base stations that is used by the PDE in computing a position fix. The important parameters that need to be defined in the BSA for each sector deployed in the network is described in Table 1.

Table 1: Base station parameters in the BSA

Antenna Center	Latitude/Longitude/Altitude of the antenna
Sector Center	Latitude/Longitude of the sector center
Transmit PN	Phase offset of the pilot transmitted by the antenna
Antenna Direction	Direction of the antenna boresight in degrees
Antenna Opening	Beamwidth of the antenna in degrees
Forward Link Calibration	The correction factor to account for the cable delays

Maximum Antenna Range	The radius up to which the signals can be detected
Frequency	The frequencies transmitted by the antenna
Repeater Flag	Used to indicate if the sector is repeated to provide coverage elsewhere

Sector Center (SC) and Maximum Antenna Range (MAR) are used extensively in the testing. The MAR is the radius (in meters) up to which the signals from the transmitting antenna can be measured and used for positioning. The SC is an imaginary point inside the sector that is considered the center of the area covered by the transmitting antenna. Typically, the SC is configured as a point along the boresight that is either one half or two thirds of the MAR away from the transmitting antenna.

2.2.2 Network based vs. Handset based positioning

Radiolocation in cellular networks can be implemented using two different approaches: network based or handset based, [12, 13]. In the network based approach, the PDE determines the location of the MS from reverse link signal measurements collected at the serving sector antenna in combination with other neighboring sectors. Since the MS is not actively involved in any stage of the location determination process, GPS solutions cannot be obtained.

In the handset based approach, measurements are collected at the handset. Both satellite based (GPS) and terrestrial base station measurements may be measured by the MS. Depending on where the actual position computation takes place, the handset based approach can be further classified as MS-Assisted or MS-Based. In the MS-Based approach the MS takes measurements and also calculates its own position. In the MS-Assisted approach, the MS relays the measurements back to the PDE for position estimation. Verizon’s cellular network, which is used for these experiments, has implemented MS-Assisted positioning.

2.2.3 Control and User Plane

When the MS's position is to be determined, the link over which communications between the base station and the MS takes place is another distinction between various positioning solutions in the market today. The control plane refers to the links of a cellular network that carries the signaling necessary for placing calls. The user plane, on the other hand, is the term used to describe the links that carry the actual voice and data traffic.

The distinction between the user plane and the control plane is relevant for the following reason. The FCC mandates a dedicated positioning system for E-911 Phase II implementation. While positioning uses essentially the same mechanisms for both LBS and 911 services, an important difference is that the positioning of 911 calls needs to be performed while simultaneously holding a voice call to the PSAP. Despite being supported by the standards, simultaneous use of voice and data is not implemented in the cellular networks [21]. This implies that the exchange of messages between the MS and the network needs to happen on the control plane link during emergency calls.

2.2.4 Positioning Algorithms

The PDE used for testing supported several algorithms that can be used to position the MS. The ones observed during testing are described below in the decreasing order of accuracy of the solution.

1. Assisted GPS (AGPS): GPS is a well-known location determination system that provides the most reliable and accurate positioning among the popular technologies available for user positioning. It uses a system of 24 satellites that precisely transmit their location and an accurate clock reference. A GPS sensor receiving signals from multiple satellites (at least 4 or 3 when altitude assistance is provided) can determine its latitude and longitude using a method called trilateration. The biggest disadvantage with this system is that the time required to acquire the position fix can be up to 13 minutes. Assisted GPS was developed [14] to improve the measurement latency and increase the signal sensitivity of the GPS receiver. The cellular network

can provide the MS assistance information consisting of the satellites that are expected to be visible to the MS based on a coarse estimate of its position. Other assistance data may include the first couple of bytes of the transmission from each satellite that can be used to extract the received signal from the noise. The type of assistance data varies with the implementation; nevertheless, it helps make the positioning better and faster. IS-801 positioning standard for CDMA uses AGPS as the primary positioning technique to satisfy the FCC Phase–II requirements for E-911 [1].

2. Advanced Forward Link Trilateration: Time can be used as a proxy for distance since light travels at a constant speed. Knowing the time it takes for the signal from a particular base station to reach the MS, the distance of the MS from the base station can be computed. Considering similar pseudorange measurements to at least four base stations as a system of equations, it can then be solved for a specific coordinate comprised of the latitude, longitude and the altitude.

3. Hybrid: If fewer than three GPS pseudorange measurements or three CDMA pilot phase measurements are available to the PDE then it is unable to compute either a GPS solution or an AFLT solution. The PDE is still able to compute a position if the combination of the two types of measurements is at least three. This type of a solution is known as a Hybrid Fix.

4. Mixed Mode: If the combination of the GPS pseudoranges and pilot phase measurements is fewer than two, the PDE returns a Mixed Mode result. This solution is computed by first calculating s Mixed Cell Sector solution and using the combination of pilot phase and pseudorange measurements to refine the predicted output.

5. Mixed Cell Sector: If the PDE is unable to compute a solution using any of the techniques mentioned above, the PDE tries to compute a position fix from the weighted average of the sector centers of the pilots reported by the MS.

6. Cell Sector: This is a special case of the Mixed Cell Sector where the MS reports only one pilot. The PDE then returns the corresponding sector center as the position of the MS.

The PDE uses a two step process to compute each fix. Each step consists of two iterations. During the pre-fix stage, the PDE first computes a solution based on the geometric overlap of the reported pilots. In the next iteration, it uses the pilot phase measurements to compute an AFLT or Mixed Mode result. Using this estimate, the PDE provides assistance data to the MS about the satellites that should be visible to the MS. The second step begins as the MS tries to measure GPS pseudoranges using the assistance information. The MS reports this information along with fresh terrestrial measurements, back to the PDE. The PDE uses these data to compute a final fix of the MS's position.

The PDE uses a metric known as the Horizontal Estimated Position Error (HEPE) to express (in meters) the uncertainty associated in the estimated solution. The MAR of the pilots used in the fix affects the HEPE. In the two iteration process to compute a solution, the PDE chooses the result of the iteration that has the lower HEPE as the solution output.

2.2.5 Pilot Beacons

A Pilot Beacon (PB) is a CDMA downlink signal that comes from a transmitter that does not carry any traffic. The beacon signal can be generated from a standalone device (a Pilot Beacon Unit, PBU). The pilot channel on the CDMA network (IS-95/2000) is modulated with the Walsh code W_0^{64}. The pilot signal acts as a reference for coherent demodulation of the forward link signal and is the first channel that is decoded in the process of receiving a downlink signal. The pilot signal is also used to notify the mobile of the presence of additional cells/sectors in the neighborhood of the mobile that can be used for soft handoff. The MS cannot tell the difference between a pilot from a CDMA base station sector and a PBU. They appear identical to a MS. If a PB is put into the neighbor list, then a mobile station will search and find this pilot. If it is strong enough, the MS will report this pilot to the network in the usual fashion with the intent to add the sector to the active set.

The network, on the other hand, is programmed to understand that the reported pilot with that particular PN phase offset is not actually a sector. But the reporting of this information provides the network with information to trigger an event based on the MS location. The key concept here is that of a trigger. Pilot beacons can be used to trigger certain events within a CDMA network. They accomplish this because the network engineer can control the location and coverage area of a PB independently of the remainder of the CDMA network. When a MS reports the PB, there is then some knowledge of the location of MS so as to trigger some desired network event. Historically, a PB serves as a trigger for two possible events of interest to CDMA network operators. The first is to manage traffic into and out of an in-building coverage system. The second is to enable better MS location determination by the network. It is this second purpose that we explore with our measurements.

Before the pilot beacons can be used for testing, they have to be integrated into the cellular network such that the network is aware of their presence and uses them for positioning. This is the most important step of the deployment process and requires careful calibration. Forward link calibration is required to set the time offset of pilot beacons and the cells in the network to the appropriate time reference. "System Time is synchronous to UTC time (except for leap seconds) and uses the same time origin as GPS time" [15]. The CDMA standard specifies that the PN offset, as it leaves the antenna, should be within ± 10 μs of absolute time referenced to GPS time standard [16]. This requirement ensures that the timing of each cell site is accurate across the network. Such synchronization is required for handoff operation for MS transitioning cells within the network.

This requirement implies that the cell equipment, and equivalently the pilot beacon equipment, should be adjustable (while on site) to have the proper time offset at the downlink antenna aperture. Other sources of delays include any delay through repeaters and DAS equipment. Any such delays may require calibration to ensure that timing is accurate as it leaves the antenna.

For positioning purposes, a similar but more stringent timing requirement is in place [2]. In [2], timing adjustments are given "in units of 1/16 TIA/EIA-95 PN chips." This implies a timing accuracy on the order of 51.0×10^{-9} seconds at the antenna element. The timing adjustment can be made physically, by adjusting the equipment timing, but timing offsets can also be incorporated into the Base Station Almanac (BSA). Within the BSA, timing offset values can be applied that will be used by the Position Determination Entity (PDE) when calculating the position of the MS. The resolution of this timing adjustment is 1/16 of a chip time. In free space, this time resolution corresponds to approximately 15.25 m. The process of Forward Link Calibration (FLC) can include both a timing adjustment at the equipment as well as the introduction of timing offset values within the BSA. The FLC process required use of SNAPCELL, a licensed software that was unavailable publicly. Verizon/Qualcomm provided assistance with the calibration process.

2.2.6 Method of Testing and Analysis:

The network frequency 887.6 MHz (Channel 630) channel was reserved exclusively for testing and not used for commercial service. This channel was disabled in Boulder and the surrounding area during testing. Verizon's service to its customers was not disrupted because their infrastructure supported service on multiple other channels. In addition, there was a need was to ensure that only the pilots specific to the particular test case would be heard by the test phones. The test phones were therefore set to access overload class (ACCL) 11 and the network redirected ACCL 11 to stay on Channel 630 always. This ensured that the phones did not switch to one of the other channels within the VZW network which would have prevented them from hearing the beacons. The beacon pilot offsets were also added to the neighbor list so that they could be reported to the PDE and used in fixes.

A mobile phone software application called Rover was installed in the test phones. Rover automated the process of initiating position determination sessions repeatedly. The tests were conducted by repeatedly initiating position requests from a set of test phones that were placed at known truth positions inside buildings and tunnels that lie within the test area. The Rover settings used for the various tests are shown in Table 2 and Table 3. The position predicted by the PDE was compared with the phone's actual true location known as ground truth, to calculate the error.

The PDE saves extensive details about each position fix that it performs in a binary format. In order to convert these logs into text files for data analysis, a Qualcomm command-line tool called TraceFilter2 was used. Based on the options passed, the tool outputs a comma seperated value (.csv) file that contains position data and a text fix summary file (.fix). These two files were used to assess the performance of the beacons in the various tests.

The position file has one line of information about the fix result of each fix performed by the PDE. The fix summary file contains detailed information about how the fix was computed including information about the initial, raw and output solution type. It shows the PNs reported by the phone and also shows the PNs used for computing the solution. Not all PNs reported by the phone may be used in computing a solution. Various checks are performed by the PDE to determine the location of the various PNs reported by the phone unambiguously. This is an important process since there is extensive PN reuse in CDMA and for the purpose of positioning the phones can measure pilots with very low signal strengths. Therefore, a situation could result where two sectors nearby can use the same PN offset.

First, the PDE performs a coverage test. Searching radially outward from the serving sector center, the PDE tries to find the antenna center of the reported PN. Measured PNs can be up to three times the MAR distance outside the sector under test. If a geometric overlap exists then the PN passes the coverage test. Next, the PDE performs a phase test to see if the phase measured by the phone is a reasonable estimate of the phase expected based on the distance of the radiating antenna from the antenna of the serving sector. If a PN passes both these tests, it may be used to compute ranging solutions like Hybrid, AFLT or Mixed Mode. If a PN only passes the coverage test it can only be used in geometric overlap based solutions like Mixed Cell Sector. Since the condition for passing the coverage test is relaxed, it is necessary to ensure that all of the pilots in the network are calibrated accurately using the FLC process.

For the purpose of analysis, two Python scripts were created. The first combines the results of the fix file and the csv file to produce a new csv file. These csv files can be processed easily using Microsoft Excel and average errors and plots can be created with ease. The second script generates a file encoded in the Keyhole Markup Language (.kml) format that can be viewed on Google Earth. Visualizing the fix distribution was a primary analysis technique as it helped identify any directional bias in the result due to the use of the pilot beacons.

Table 2: LBS Rover Settings for Collecting User Plane Data

Test Settings	**Description**	**Value**
Set Accuracy	Request accuracy: Range: 1-6	6
Set Request Type	Allowed values: “Location”, “Velocity” or “Altitude”	Location
Set GPS Mode	Allowed values: “One shot”, “Track Local”, “Track Network”, “Download first”.	Track network
Set GPS QoS	Quality of Service: Range: 1-255	0: GPS off, 16: GPS on
Set GPS Optimization	Allowed values: “Speed” and “Accuracy”	Accuracy
Set Number of Fixes	Number of fixes to request. 0 for infinite	120
Set Interval	Estimated interval (in seconds) between two fixes	1
Set GPS Server	URL and port number for the PDE server.	

Table 3: LBS Rover Settings for Collecting Control Plane Data

Test Settings	**Value**
Dial String	923
Call Setup Time	5 sec
Call Hold Time	45 sec
Time Between Calls	30 sec
Number of fixes	TBD

CHAPTER 3

Indoor Locations with Outdoor Beacons - 1

3.1 Introduction

In an indoor environment, GPS signals are weak or even unavailable. In such cases, the positioning method would default to one of the techniques based on CDMA pilot measurements explained earlier. If a wireless carrier were to deploy beacons to assist with the indoor positioning needs, covering multiple buildings with a single beacon would be most desired from an economic point of view. Hence, the first scenario tested in evaluating the effectiveness of pilot beacons was an outdoor deployment of beacons covering a section of campus near the engineering center. This type of deployment covers a majority of the indoor positioning needs where users are distributed over a wide area such as in residential or office buildings or a campus environment.

The objective of this phase of testing was to investigate the hypothesis that beacons help improve indoor positioning. To verify this claim, experiments were conducted by turning ON beacons successively in various combinations so that the performance change from one configuration to another can be compared.

3.2 Setup

Similar to GPS based positioning, at least four points of reference are required to position users in three dimensions, but this study is limited to the analysis of horizontal positioning that is required by the FCC mandate [1]. This relaxes the requirement on the number of points of reference required to three. With that in mind, one of the first decisions that had to be made was site selection for the pilot beacon installation and indoor locations for testing. These sites were required to be, primarily, in the neighborhood of "Whizzer"[1] since it was used as the serving sector for most of the tests. However, there were a few tests conducted which involved Bison as the serving sector also.

Due to the thick stone walls and multiple small rooms of the campus buildings, there is a lot of attenuation of signals arriving from outside. Having to pass through one building to reach the next would increase the transmit power requirement. This causes the MS in the immediate neighborhood of the beacon to drop calls if not collocated with a BTS. If the beacon pilot is stronger than the traffic pilot, a MS would unsuccessfully try to handoff to the beacon pilot. Therefore, candidate sites for beacon deployment were high-rise buildings. The Engineering Center tower (ECOT), Folsom Stadium (Folsom), the Speech Language and Hearing Sciences (SLHS, building on a small hill) and the JILA tower were initial candidates. JILA was later excluded since it almost overlapped with one of the Verizon base stations and would not provide good angular diversity. Finally, an off-campus building (SAN MARCOS), a high rise condominium building opposite the Regent Administrative Center, was chosen since it provided good angular diversity. The importance of angular diversity will become apparent when the results of these tests are discussed in later sections. The pilot beacon locations are marked by the letter 'B' in Fig. 2 below.

The next step was the installation of the beacons. The beacons used for testing were prototype versions intended for lab testing and were loaned for this field testing effort. An important step before deployment was to weather-proof these beacons. This was accomplished by enclosing the beacons in a weather-proof plastic box with all necessary cabling and power distribution boards as shown in Fig. 3. These boxes were bolted to wooden planks and sand bags were used to provide ballast against possible heavy winds. Finally, the telnet interface available in the beacons was leveraged to enable remote

[1] Whizzer and Bison are the names of two VZW cell sites on or near the CU campus. Each of these cell sites had three sectors and the sectors used for testing are shown in Fig. 2

reconfiguration by adding wireless modems. The transmit antenna and the GPS sensor antenna were mounted outside of the box.

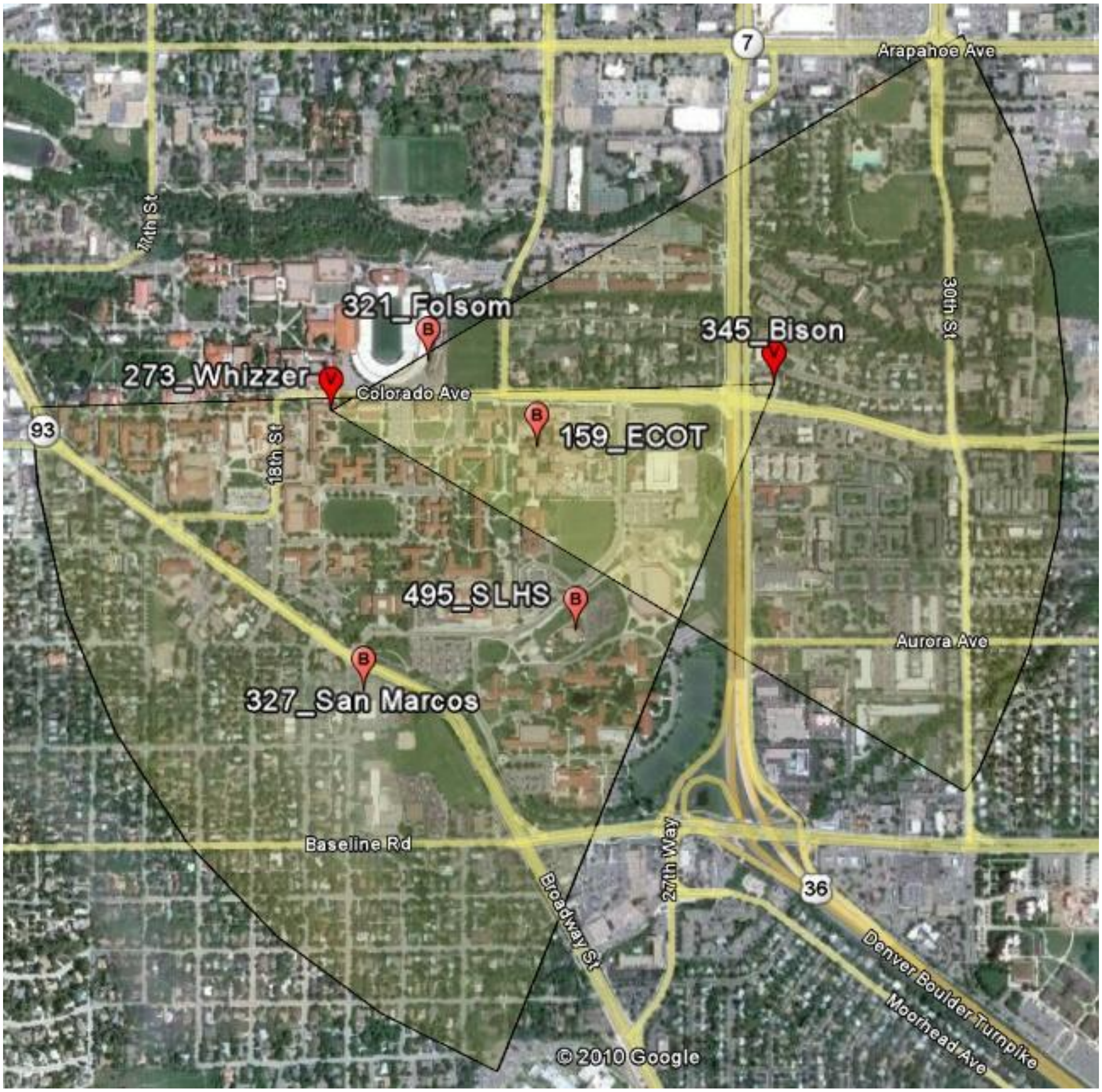

Fig. 2: PBU locations relative to existing Verizon sectors

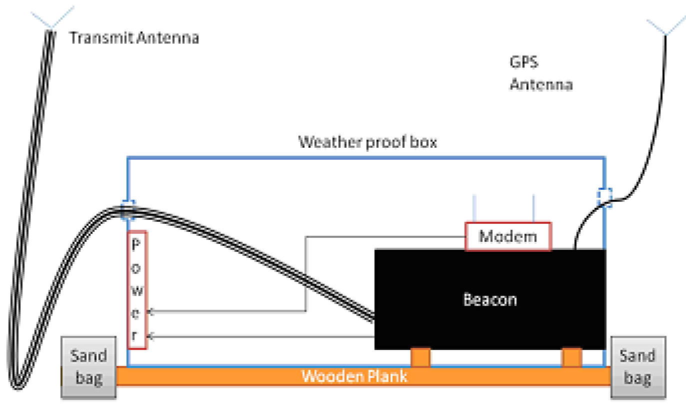

Fig. 3: Weather-proofing for outdoor PBU

As shown in Fig. 3, the four beacons formed an irregular quadrilateral pointing inward. Except for the omnidirectional antenna used at ECOT, the other test locations all had panel antennas with a 70 degree horizontal beam width.

The following table provides a summary of the pilot beacon configuration:

Table 4: Pilot Beacon Configuration for outdoor deployment

Parameter	**Value**
Channels Used	1
Transmit Power	+19 dBm (max) for outdoor beacons
Transmit Channel	Channel 630 (889.6 MHz)
PN Offset	One per beacon: 159, 321, 327, 495
Tau Offset	Values as determined by FLC

The Tau offset refers to the timing adjustment at the beacon for calibration. The test locations were chosen such that all four beacons were heard when turned ON. Two residence halls, Reed and Cockrell, and the Leeds School of Business were chosen for testing. The test locations are shown in Fig. 4 along with the beacon locations.

Pilots used for position determination can be heard at lower levels of Ec/Io than traffic pilots. For the purpose of position determination, phase measurements of pilots with Ec/Io as low as -29 dB are usable while the traffic pilot needs to be significantly stronger at Ec/Io of -15 to -16 dB. Hence, the pilot beacon transmit power was set to 19 dBm.

Fig. 4: Test Locations

3.3 Tests Performed

Tests were performed with just Whizzer or with Whizzer and Bison. Positioning was studied by using various combinations of beacons. The tests performed are listed in Table 5 and Table 6.

For each test set ID, the configuration of the pilot beacons and sectors that were transmitting are shown in the tables. The number in the PB column is the MAR value for that beacon. Any MAR value not left empty for a beacon indicates that the beacon was used in the test with the MAR value set in the BSA as specified. All MAR values are given in units of meters. The 'X' in the Whizzer/Bison column indicates that the corresponding VZW sector was used in the test configuration.

During these tests, three test phones with phone numbers ending in x4597, x1396 and x0428 were placed at COC, Reed and Leeds, respectively. The test set was conducted by initiating approximately 120 position fix requests from each phone (simultaneously) using the Rover application on the phone. The measurement fixes were collected at the PDE data center and made available for post processing. Each configuration (test set) produced a distribution of fix (position) solutions after post processing.

Table 5: Indoor Tests, Set 1

Test Set	ECOT PN159	Folsom PN321	San Marcos PN327	SLHS PN495	Bison PN345	Whizzer PN273
1A-1						X
1B-1				1000		X
1B-2	1000					X
1B-3			1000			X
1B-4		1000				X
1C-1	1000			1000		X
1C-2		1000		1000		X
1C-3			1000	1000		X

Test Set	ECOT PN159	Folsom PN321	San Marcos PN327	SLHS PN495	Bison PN345	Whizzer PN273
1C-4	1000		1000			X
1C-5	1000	1000				X
1C-6		1000	1000			X
1D-1		1000	1000	1000		X
1D-2	1000		1000	1000		X
1D-3	1000	1000	1000			X
1D-4	1000	1000		1000		X
3E-1	1000	1000	1000	1000		X

Table 6: Indoor Tests, Set 2

Test Set	ECOT PN159	Folsom PN321	San Marcos PN327	SLHS PN495	Bison PN345	Whizzer PN273
2A-1					X	X
2B-1				1000	X	X
2B-2	1000				X	X
2B-3			1000		X	X
2B-4		1000			X	X
2C-1	1000			1000	X	X
2C-2		1000		1000	X	X
2C-3			1000	1000	X	X
2C-4	1000		1000		X	X
2C-5	1000	1000			X	X
2C-6		1000	1000		X	X

Test Set	ECOT PN159	Folsom PN321	San Marcos PN327	SLHS PN495	Bison PN345	Whizzer PN273
2D-1		1000	1000	1000	X	X
2D-2	1000		1000	1000	X	X
2D-3	1000	1000	1000		X	X
2D-4	1000	1000		1000	X	X
2E-1	1000	1000	1000	1000	X	X

3.4 Results

The data collected were processed using Tracefilter2 and plots of the fix distribution were made using Google Earth. In addition, the average, standard deviation, minimum and maximum values of error and uncertainty in the fix were calculated for each test location. From a total of 11,566 valid fixes, all but four had Whizzer as the serving sector.

To simplify the analysis, the various tests can be grouped by the number of pilots present in the test. With two cellular sectors and four beacons there could be a total of up to six pilots.

3.4.1 Tests Reporting One Pilot

The phones only reported the serving sector (Whizzer: 273) and no other pilots were reported. With just one pilot, it is expected that the PDE would produce a Cell Sector position with all fixes being at the sector center marked in Fig. 6. Instead, a Mixed Cell Sector (MCS) solution was produced with almost all fixes coinciding at a set of 8-10 points along the boresight of the antenna as seen in Fig. 6. It was also observed that these points were spaced 15 meters apart, which corresponded to $1/16^{th}$ of a CDMA chip. The Qualcomm chip used in the test phones can measure pilot phase with a resolution of up to $1/16^{th}$ of a chip [14]. Deeper investigation into the individual fix records (logs) generated by the PDE revealed that the PDE used additional position aiding round trip delay measurements while computing a

MCS fix. In the absence of any angle information, the PDE uses round trip delay measurements to provide a solution along the sector center line closer or further than the sector center from the antenna center. Therefore, the resolution of round trip measurement caused the orderly distribution of the fixes. With just one range measurement, all the results are constrained on the axis along the antenna boresight. An important thing to note is that the positioning error for these types of fixes is dependent on the location of the test point. Although all three test locations were between 350-450 m from Whizzer, a sector could cover over 1.5 miles. Thus, the error for a ground truth location at the sector edge would be manifolds greater as shown in Fig. 5. The HEPE metric, which is a measure of the confidence of the PDE in its solution, supports this statement. The uncertainty in the solutions using just one pilot was about 1000 meters. Such predictions with high uncertainty are of limited use in E-911 without the caller's input to the PSAP about his/her location. Further, such high uncertainties are completely useless in turn by turn navigation applications when the user's current position affects the selection of the route to the destination. The user would have to wait until he/she steps outdoors before the navigation application is able to start suggesting routes.

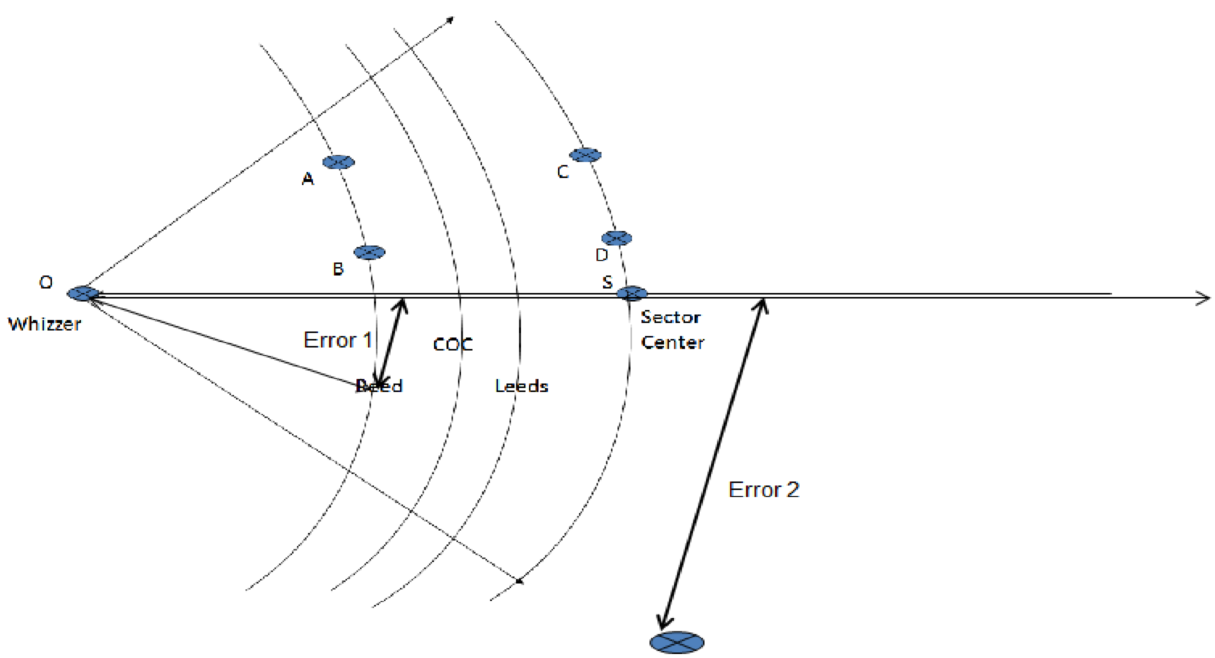

Fig. 5: Possible errors in a MCS solution

Fig. 6: Fix distribution for MCS solution using only Whizzer

3.4.2 Test Reporting Two Pilots

Here the phones report another pilot in addition to the serving pilot. This could be a beacon or a sector. When less than three pseudorange measurements are available, it is expected that the PDE would compute a solution of type Mixed Mode which combines the sector coverage information with the pseudorange measurements to produce a position estimate. Mixed Mode fixes are expected to have a greater accuracy than MCS. It was observed that the addition of a beacon improved indoor positioning accuracy.

Fig. 7 shows the fix distribution at the three test points due to each of the four beacons that were turned ON alternately. Solutions were “dragged” towards whichever beacon was transmitting. Fig. 7 provides an insight into the working of the PDE. The sector center entry in the BSA plays an important role in the fix computation. For an omnidirectional beacon, the sector center coincides with the antenna location. On the other hand, the sector center for a 60 or 70 degree sector will be defined further out along the boresight. A suitable arrangement may be possible whereby aligning the boresight of the beacons with the area of maximum MS density and suitably adjusting the sector center in the BSA could pull fixes towards the most probable area where a call can originate. However, this technique is not foolproof as calls from other areas covered by the pilot would get positioned erroneously along the boresight.

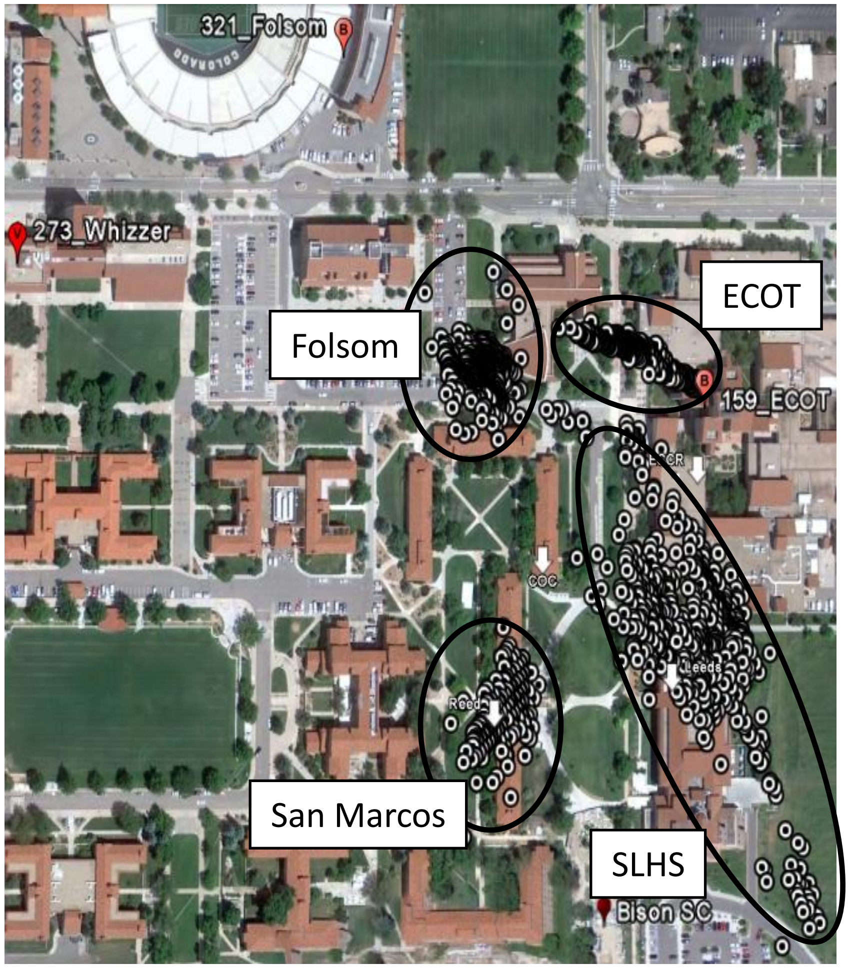

Fig. 7: Fix distribution for MM solution using Whizzer and one of the four beacons

3.4.3 Tests Reporting Three or More Pilots

If three or more pilots are reported by the phone, it is expected that the PDE would produce AFLT solutions. AFLT is expected to have considerably better accuracy than Mixed Cell Sector or Mixed Mode. It was observed that on average AFLT fixes were better than Mixed Mode fixes by 40 meters. The comparison of the errors resulting from the use of different algorithms is shown in Table 7.

Analyzing a step further, as shown in Table 8, the AFLT results were separated for three, four, five and six pilots since the number of fixes with three pilots was predominant. As a result the average error was biased towards the average error for three pilots. Accuracies actually improved by 8.55, 7.28, 12.74 meters due to the addition of each successive beacon. It was also observed that the uncertainties in solution reduced progressively.

Table 7: Combined results from the three test locations (meters) with three or more pilots

Combined results from three test locations (in meters)			
Error			
	MCS	**MM**	**AFLT**
Mean	203.113	140.483	101.34
Std Dev	41.366	49.8881	51.7045
MIN	72.9731	1.00225	0.7912
MAX	239.091	327.683	422.095
Count	519	2674	8373
HEPE			
	MCS	**MM**	**AFLT**
Mean	971.529	409.471	257.741
Std Dev	87.3576	57.8345	71.636
MIN	661.7	236.5	54.6
MAX	1283.9	766.7	588.1
Count	519	2674	5484

Table 8: Combined results from the three test locations (meters) with three or more pilots

Combined results from three test locations (in meters)				
Error				
	3 Pilots	**4 Pilots**	**5 Pilots**	**6 Pilots**
Mean	106.7046286	98.14824856	90.86948362	78.12990056
Std Dev	47.6633137	57.28526033	53.40893371	36.40577609
MIN	4.656393454	1.541492783	0.791201618	6.192648868
MAX	307.6760585	422.0948796	314.8738619	175.239925
Count	4538	2615	967	253
HEPE				
	3 Pilots	**4 Pilots**	**5 Pilots**	**6 Pilots**
Mean	287.1134861	244.8048184	210.1019648	184.1944664
Std Dev	58.53204468	70.76710268	66.29440422	44.80007906
MIN	169.4	92.9	54.6	108.6
MAX	813.8	495.4	424.3	320
Count	4538	2615	967	253

The values that are of greater interest are the errors with 67% and 95% probability. The cumulative distribution function in Fig. 8 and the adjoining Table 9 show the 67th and 95th percentile errors in comparison to the FCC mandated values.

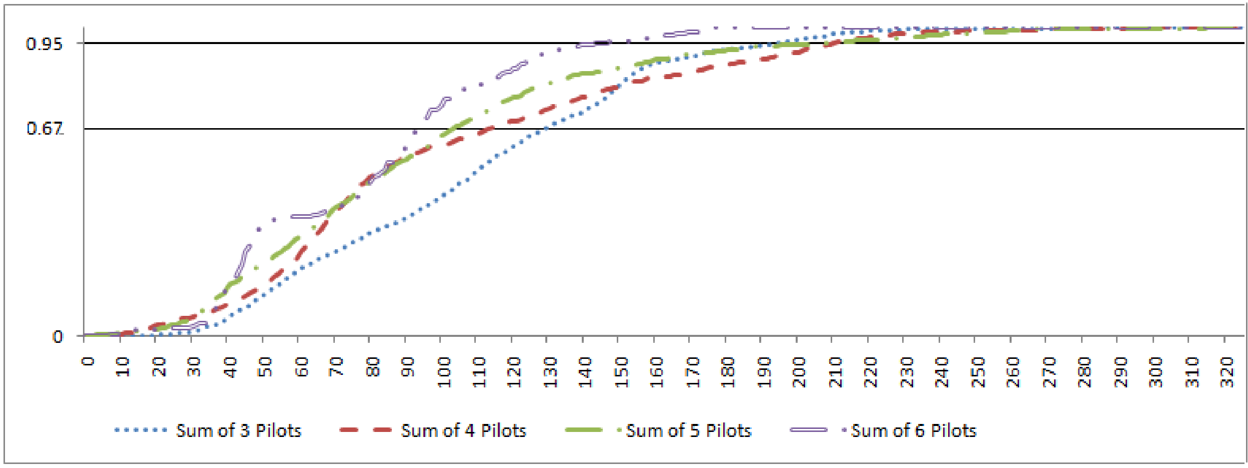

Fig. 8: CDF plot of error in meters for a given number of pilots measured by the MS

Table 9: 67th and 95th percentile errors (meters) in comparison to the FCC mandate

Pilots	Error 1 (67%)	Error 2 (95%)
3	128	195
4	113	210
5	103	208
6	93	146
FCC	50	150

Performance gains due to the addition of beacons occur for the following reasons:

1. Improved geometry: In the case of MCS fixes, a specific combination of beacons may cause the truth position to fall inside the region of overlap of their coverage. This produces a very low error in the MCS result. In the case of AFLT, signals from specific beacons may have a better RF path to the test location, resulting in phase measurements that are more accurate measures of the distance from the signal source. This leads to better AFLT results. This is best illustrated in the data summarized in Table 20 in the Appendix. On both test sets, the San Marcos beacon performed very well. The addition of San Marcos to one, two and three other beacon(s) always

produced improvements in accuracy. The flip side of this effect is also true, and the addition of other beacons may worsen the error due to unfavorable geometry. Folsom is an example of a beacon that worsens accuracies.

2. Change of algorithm used in solution: There is a definite improvement in both positioning accuracy and uncertainty of the fix when it changes from a Mixed Cell Sector to a Mixed Mode or from a Mixed Mode to an AFLT. Fig. 9 shows the average error by fix type. Among the non-GPS fixes, AFLT fixes perform the best and Mixed Cell Sector fixes perform the poorest.

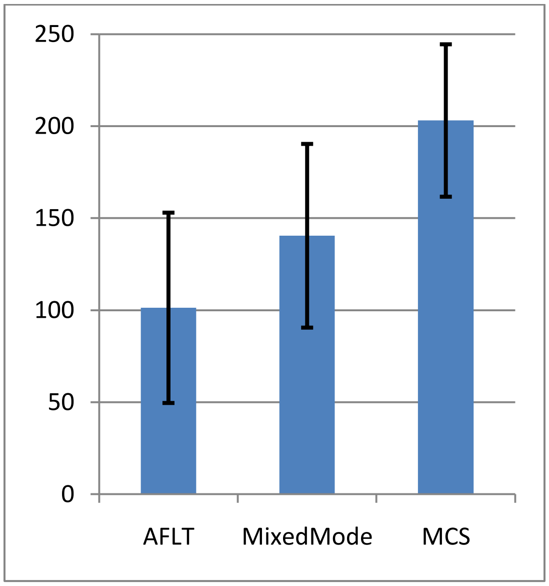

Fig. 9: Error distribution by fix type

CHAPTER 4

Indoor Locations with Outdoor Beacons -2

4.1 Introduction

In the previous section, when the number of ranging pilots was limited, the effect of a single pilot on the final solution was evident. The addition of a beacon forced solutions to be closer to the beacon. In all of the earlier tests, the beacons had the same MAR value. It would be interesting to know if beacons with smaller MARs have a significantly greater impact on the final solution (error and uncertainty) than when beacons have the same MAR as the transmitting base stations.

4.2 Setup

The beacon locations and the test locations from the previous experiment were retained for these tests. In these tests, the Leeds test location was swapped with a test location in the engineering center (ECCR) since it was directly under the beacon.

4.3 Tests performed

Tests were performed with just Whizzer or with just Bison. In addition, beacons 159 and/or 495 were turned ON. Also, the MAR values listed in Table 10 for each beacon were set in the BSA and loaded into the PDE before the start of each test. As with the previous test description, an empty entry for the MAR indicates the beacon was OFF. All MAR values are given in units of meters.

During these tests, test phones with phone numbers ending in x4597 and x1396 were placed at COC, Reed at first. Later the entire set of tests was repeated at ECCR using both phones. The test set was conducted by initiating approximately 120 position fix requests from each phone (simultaneously) using the Rover application on the phone. The measurement fixes were collected at the PDE data center and made available for post processing. Each configuration (test set) produced a distribution of fix (position) solutions after post processing.

Table 10: Indoor Tests, Set 3

Test Set	**ECOT PN159**	**Folsom PN321**	**San Marcos PN327**	**SLHS PN495**	**Bison PN345**	**Whizzer PN273**
3A-0					X	
3A-1	1000				X	
3A-2	50m				X	
3B-1				1000	X	
3B-2				50m	X	
3C-1	1000			1000	X	
3C-2	50m			50m	X	
3D-1	50m			1000	X	
3D-2	1000			50m	X	
4A-0						X
4A-1	1000					X
4A-2	50m					X
4B-1				1000		X
4B-2				50m		X
4C-1	1000			1000		X
4C-2	50m			50m		X
4D-1	50m			1000		X
4D-2	1000			50m		X

4.4 Results

4.4.1 Only one Beacon ON with a MAR value of 50

This test includes cases where one beacon has a MAR value of 50 while the other is off. It was observed that the beacon dominated the solution, resulting in fixes that were coincident with the beacon location. Although the fixes were Mixed Mode with both Whizzer and ECOT or SLHS being used, the distribution was similar to a Cell Sector result with an omnidirectional sector transmitting PN159. Fig. 10 shows fixes when ECOT is ON and Fig. 11a shows fixes when SLHS is ON. Irrespective of the test location, the fixes were coincident with the beacon.

Fig. 10: Fix distribution for ECOT with a MAR value of 50 while SLHS is OFF

4.4.2 Only one Beacon ON with a MAR value of 50 vs. a MAR value of 1000

A comparison of these two tests shows the bias in the result introduced by altering the MAR. Although the phone reported the same beacon in both these tests, the PDE provides a different result. It is evident that the PDE uses the MAR value when computing the result since in the case where the MAR was reduced to 50 meters, the PDE drew the fixes closer the SLHS in an attempt to satisfy the fact that a beacon can be reported only if it can be heard. On the other hand, when beacon MAR was set more realistically, the solution had a larger spread and the error from the ground truth was smaller. This is illustrated in Fig. 11.

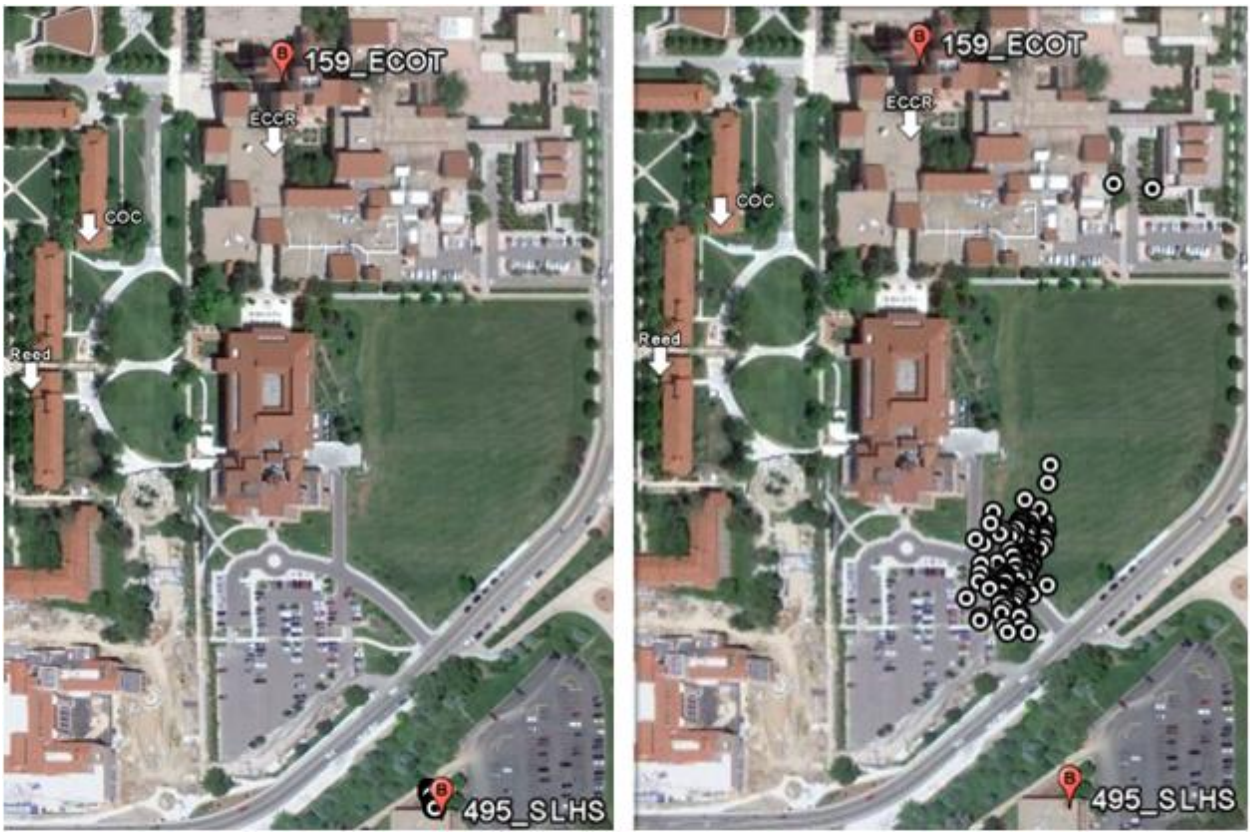

Fig. 11: a. Fix distribution for SLHS with a MAR value of 50 while ECOT is OFF, b. Fix distribution for SLHS with a MAR value of 1000 while ECOT is OFF

4.4.3 Two Beacons ON; one with a MAR value of 1000 and the other with a MAR value of 50

The results in these tests were also similar to the case when the beacon with a higher MAR was OFF as observed in Fig. 12. Now, with three ranging sources the PDE was able to compute AFLT solutions. The results were contradictory to the expectation that the PDE would just use the pseudorange measurements and ignore the MAR values since AFLT is a ToA/TDoA based algorithm. Even with

AFLT type fixes, it was observed the PDE biased the results based on the assumption that if a phone reported a PN it must be within radio range, defined by the MAR.

Fig. 12: a. Fix distribution for SLHS with a MAR value of 50 and ECOT with a MAR value of 1000, b. Fix distribution for SLHS with a MAR value of 1000 and ECOT with a MAR value of 50

4.4.4 Two beacons ON; both with a MAR value of 1000 or a MAR value of 50

In Fig. 13, the results of using Bison along with the two beacons are shown. These measurements were made at Reed. When the MAR value of both the beacons is 50 meter each, the distribution has a low East-West spread indicating that the impact of measurements from Bison was low. All the fixes were parallel to the straight line connecting the two beacons.

When the MAR value of the beacons is relaxed to 1000 meters each, measurements from Bison start playing a role in the result. This leads to a positive effect since the fixes are closer to the truth location (Reed). Another side effect of relaxing the MAR is that the noise in the pseudorange measurements of Bison show in the distribution of the fix.

It is clear that a large MAR is more accurate and less precise (HEPE >300 meters) while a small MAR is less accurate and more precise (HEPE < 150 meters). The Table 11 presents the average and standard deviation for the different combinations of MAR value for the two beacons. A comparison of these two test cases brings out an important rule that altering beacon MAR values in the BSA to make them smaller than what is realistic is not useful for positioning users spread over a large area in multiple buildings. The only case when a beacon deployment with a small MAR would benefit positioning is when users are present in a small area and the transmit power is actually scaled down to just cover the area.

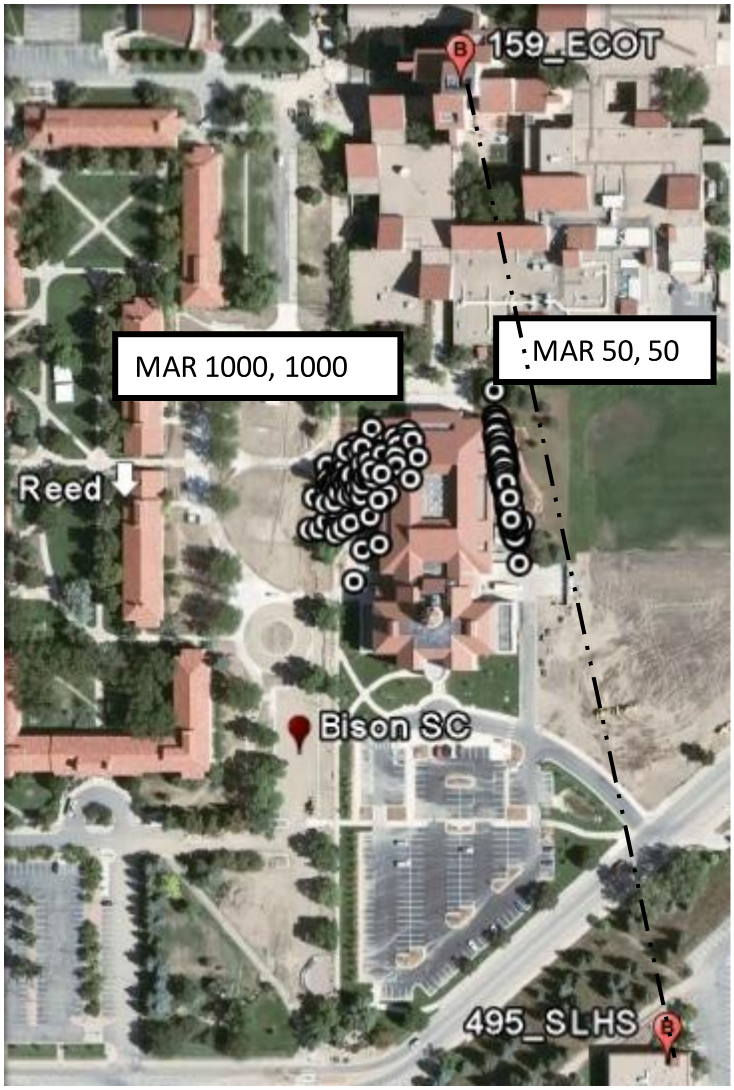

Fig. 13: Fix distribution for both beacons with a MAR value of 50 or a MAR value of 1000

Table 11: HEPE variation over different MAR value combinations for ECOT and SLHS

Beacon 1 MAR	1000	50	1000	0
Beacon 2 MAR	1000	50	50	50
Average	309.0136	134.3542	27.328	17.08167
Std Dev	24.4581	10.4424	3.266514	2.162097

CHAPTER 5

Tunnel Environment

5.1 Introduction

The most common tunnels of interest to a wireless carrier are long vehicular tunnels, such as might be found in a rail network. Purely pedestrian tunnels, where users expect to have cellular coverage, are also of interest to the carrier. Such tunnels may be found underground connecting commercial buildings like airport terminals. From a positioning point of view, these locations have the common attribute that a MS in the tunnel is not illuminated by external RF sources. This also implies that MS have no view of GPS signals and also have no ability to receive signals from local base stations that are external to the tunnel.

Service for MS in the tunnel would only be available from an RF signal source that was brought into the tunnel by the cellular operator. This is done in one of two typical ways. The first option is to use a dedicated base station in conjunction with a distributed antenna system (DAS). The distributed antenna system may use either leaky coax antennas or antenna units at various locations along the tunnel. Alternatively, the tunnel may be illuminated by an antenna at the mouth of the tunnel fed by a repeater which rebroadcasts signals from an external base station.

There are a number of problems in positioning users in a tunnel environment. If the tunnel is fed from an external sector through a repeater then it is presumed that this external sector also serves MS that are outside of the tunnel. The repeater introduces additional delays in the arrival of signals within the tunnel. This distorts the time of arrival based positioning that the PDE uses when it computes an AFLT solution. Any BSA entries must reflect the need to also position MS outside of the tunnel. That is, one cannot define the radiation center of the sector in the tunnel or at the mouth of the tunnel or alter FLC values to reflect the repeater delays.

A tunnel served by a dedicated base station has the ability to define the BSA parameters like sector center, MAR and FLC specific to the tunnel without regard to users that are outside of the tunnel. Even with this configuration, the indoor base station is the only pilot that the MS sees. The lack of pilot diversity prevents the PDE from calculating accurate position results.

Testing was performed in a tunnel environment in order to determine if pilot beacons can be used to alleviate the problem of positioning users in tunnels. Tests were designed to explore pilot beacon based positioning in repeater fed deployment as well as a dedicated indoor base station deployment.

5.2 Setup

For testing the linear configuration of pilot beacons which would be the case in vehicular tunnels, the network of service tunnels under the CU campus was used. A tunnel that runs along the west side the Engineering Center was chosen for the experiments. The tunnel extends towards the south for approximately 250 meters along the Koelbel building. It is a utility tunnel that is used to provide utility and telecommunications connectivity between buildings on campus. Compared to vehicular tunnels, the utility tunnel is extremely narrow but it provides the required isolation from the outdoor environment. Therefore, even when repeating signals from the macro network into the tunnel there would be no concern that the direct signals might interfere with the testing. Furthermore, even in vehicular tunnels, if it can be ascertained that a MS is definitely inside the tunnel, the problem of positioning users is reduced to determining the location offset from the entrance.

As explained in the previous chapters, the approach towards positioning was to use several beacons along the length of the tunnel, each with a very small MAR. A 100 meter section of the tunnel 20 meters from the entrance was chosen and three truth positions beacons were deployed at 20 meters, 70 meters and 120 meters from the entrance. Just two emitters would be sufficient to cover the tunnel. These beacons were broadcast from the antennas at (X1, Y1) and (X2, Y2). Signals from Whizzer were chosen to be repeated into the tunnel using a Yagi-Uda antenna to provide traffic service. The repeated signals were fed into a fiber optic DAS. The deployment setup is shown in Fig. 14. The DAS system consisted of three Corning DAS Head End Units (HEUs) each of which modulated light based on one RF input. The signals were distributed to remote locations along the length of the tunnel and were converted back to RF using a Remote Antenna Unit (RAU). These signals were fed into omnidirectional antennas.

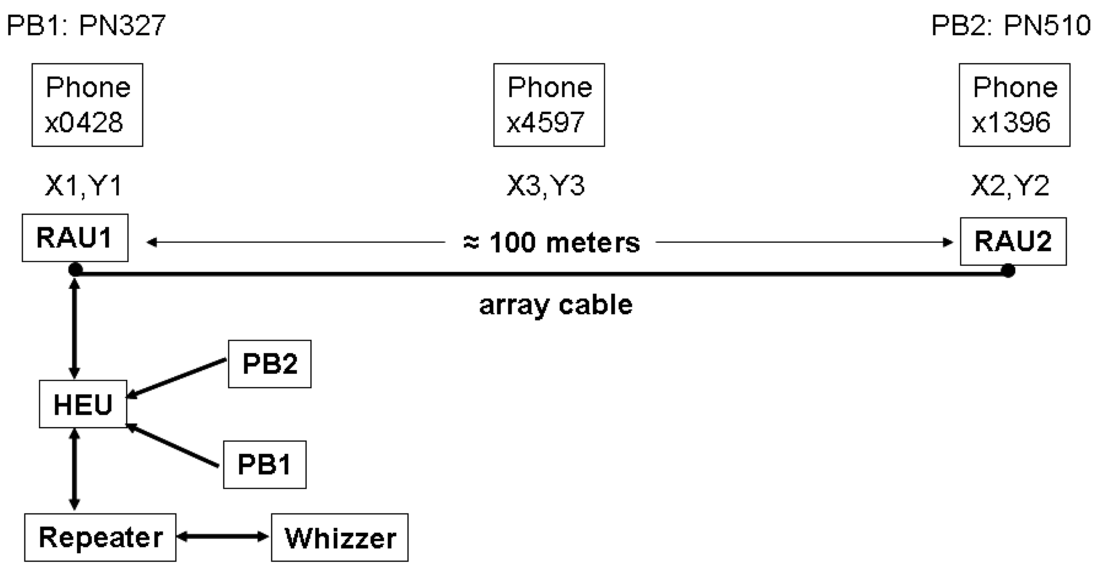

Fig. 14: Equipment configuration and test locations for tunnel tests

The following table shows the beacon configuration used.

Table 12: Beacon configuration

Parameter	Value
Channels Used	1
Transmit Power	+ 6 to 10 dBm
Transmit Channel	Channel 630 (889.6 MHz)
PN Offset	One per beacon: 327, 510

Parameter	Value
Tau Offset	Values as determined by FLC

Two different pilot beacon signals were emitted from positions (X1, Y1) and (X2, Y2). Whizzer was emitted from locations (X1, Y1) and (X2, Y2) along with PN offsets 327 and 510 at (X1, Y1) and (X2, Y2) respectively. The tunnel is actually under the sidewalk right outside the engineering building as shown in Fig. 15 with the solid yellow line. The transmitter positions were incorrectly entered in the BSA with a 20 meter offset to the west of the actual locations.

While this offset is regrettable it had no effect on the results. This is true because the radiation centers of the pilot beacons as well as the truth positions of the test phones were all treated with the same offset in the BSA. Since GPS was turned off, there was no external positioning reference information that the phone could use. The PDE computed all the position fixes with a 20 meter offset towards the west based on the BSA information.

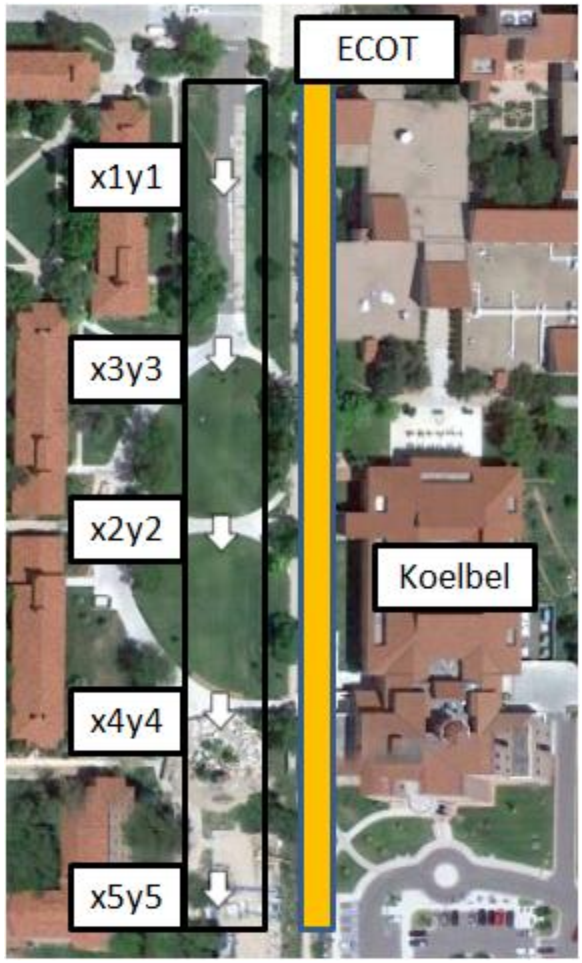

Fig. 15: Test locations modeled relative to the actual tunnel location in yellow

5.3 Tests performed

The objective of this set of tests is to demonstrate that when pilot beacons are deployed along a tunnel using a DAS, subscribers along the tunnel will be located to the portion of the tunnel covered by the pilot beacon. The following tests cases were executed as shown in Table 13. The MAR values are given in units of meters.

For each test, the antenna center indicates the location of the radiation center/sector center (equivalent for omnidirectional antennas) that was entered into the BSA. The location (a,b) was the position outside of the tunnel that Whizzer used normally when serving non-tunnel users.

Comparing the values of the traffic antenna center, it can be observed that test cases T1-T6 exercised the case in which the tunnel was modeled as being illuminated by a dedicated sector with a radiation center at truth position (X1, Y1). In the case of test T3, the radiation center was modeled to be in the tunnel 1 kilometer to the north of (X1, Y1). (The tunnel was not really this long but the BSA entry will emulate such a long tunnel). In the test cases T7-T9, the environment is modeled as being fed by an external sector such that the BSA entry for the sector remains unchanged (external to the tunnel) in order not to affect performance for the macro cell users.

During these tests, three test phones with phone numbers ending in x0428, x4597 and x1396 were placed at locations (X1, Y1), (X2, Y2) and (X3, Y3), respectively. Each test required specific BSA entries as shown in Table 13. The test was conducted by initiating 120 position fix requests from each phone (simultaneously) using the Rover application on the phone. During the tests, test personnel were in the tunnel to operate the phones but there was no movement during the testing. Fig. 14 shows the test truth positions along with an approximate outline of the tunnel as modeled in the BSA.

Table 13: Tunnel tests

Test	**Antenna Center**			**MAR**		
	PB1 PN327	**PB2 PN510**	**Whizzer**	**PB1**	**PB2**	**Whizzer**
T1	X1, Y1	X2, Y2	X1, Y1	66	66	100*
T2	X1, Y1	X2, Y2	X1, Y1	66	66	1000*
T3	X1, Y1	X2, Y2	1 km north of X1, Y1	66	66	1000*
T4	X3, Y3	X2, Y2	X1, Y1	50	66	100*
T5	X3, Y3	X2, Y2	X1, Y1	50	66	1000*
T6	X3, Y3	X3, Y3	X1, Y1	50	50	100*
T7	X1, Y1	X2, Y2	a,b	66	66	2700

Test	Antenna Center			MAR		
	PB1 PN327	PB2 PN510	Whizzer	PB1	PB2	Whizzer
T7a	X1, Y1	X2, Y2	a,b	66*	66*	2700
T7b	X1, Y1	X2, Y2	a,b	66*	66*	2700*
T8	X3, Y3	X2, Y2	a,b	50	66	2700
T9	X3, Y3	X3, Y3	a,b	50	50	2700
T9a	X3, Y3	X3, Y3	a,b	300	300	2700

* Indicates that the In-Building Flag was set in the BSA for that downlink signal source

5.4 Results - Tunnel Served By a Dedicated Sector

5.4.1 T1, T2, T3

Tests T1, T2, and T3 explore the influence of the MAR value of the traffic sector relative to the MAR value of the pilot beacons. Between tests T2 and T3, the location of the radiation center for the traffic sector was moved to the north by 1 kilometer. Again, the relative weights of the MAR values along with the distance of the MS from the radiation center become relevant when comparing T3 to T2.

The expected result from these comparison tests was to find that as we transition from the configuration for test T1 to T3, the weight of Whizzer on the final solution should decrease.

Consider phone x1396 which was positioned at truth position (X2, Y2). Since Whizzer had the in-building flag set, it was not used in ranging. All of the fixes were of type MCS. The influence of Whizzer can be seen by considering Fig. 16.

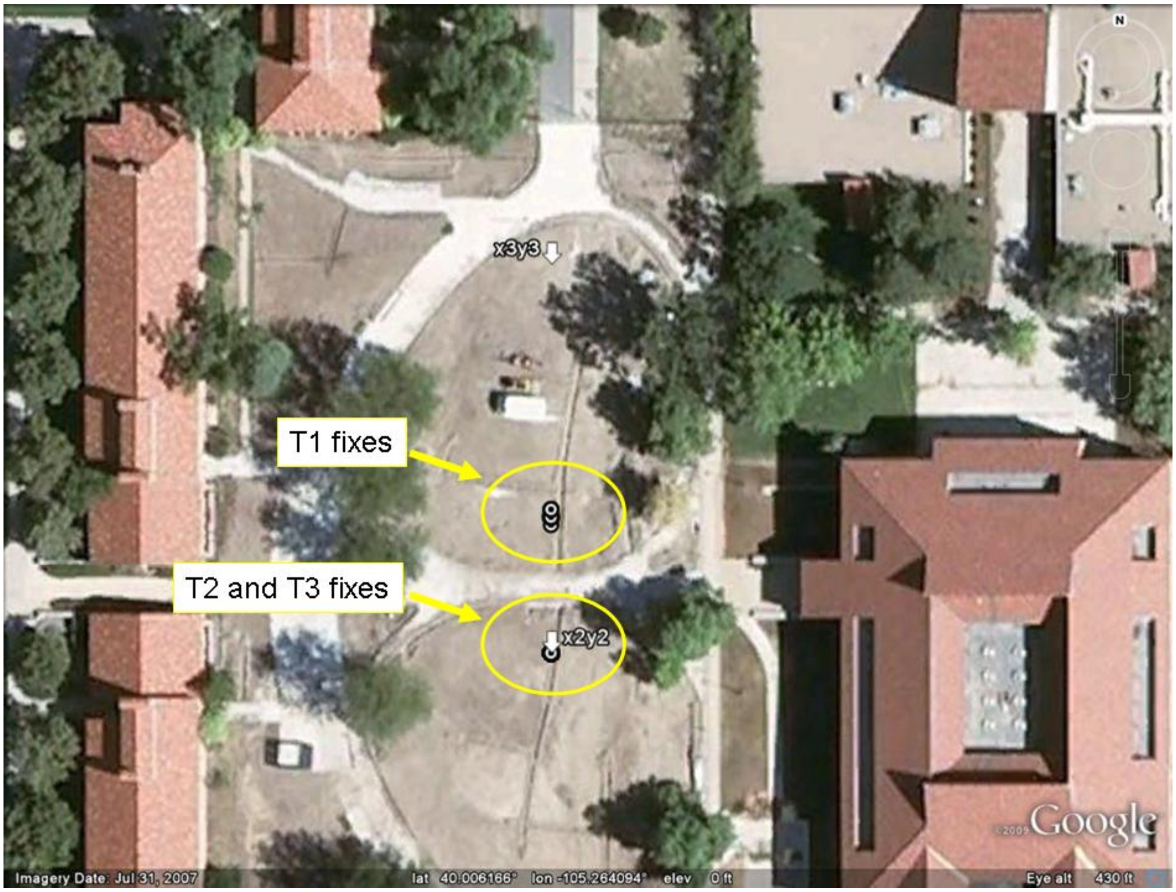

Fig. 16: Phone x1396 Fix Distribution for Tests T1, T2 and T3

Note that there are over one hundred fixes for each test case T1, T2 and T3. The results in Fig. 16 show that these fixes are greatly overlapping at their respective positions such that only a single point (three in the case of T1) is visible in the diagram.

As we move from test T1 to T2 and T3, we note that the MAR value of Whizzer changes from 100 meters (the approximate length of the tunnel) to 1000 meters (much larger than the tunnel). The key is that the 1000 meter MAR is much greater than the 66 meter MAR of the pilot beacon PB2 (PN510). The relative weight of the MAR value is proportional to the inverse ratios of the MAR. In other words, the larger MAR for the serving traffic tunnel sector puts a larger weight to the MAR value of the beacon. This puts the fix results of T2 and T3 closer to the beacon at (X2, Y2).

Phone x4597 was positioned at truth position (X3, Y3). Since Whizzer had the in-building flag set, Whizzer was not used for ranging in any of the fixes. The fix type for x4597 was of type Mixed Mode, with both PB1 and PB2 (PN327 and PN510) being used for ranging in the fix solution. The range of solutions x4597 for tests T1, T2 and T3 is shown in Fig. 17.

It should be noted that the solutions for T1 are shifted towards Whizzer which is modeled as having a radiation center at (X1, Y1). This is similar to the observation for phone x1396. Solutions for T3 shifted slightly less toward Whizzer while solutions for T2 are more centered at (X3, Y3).

All of the solutions for T1, T2 and T3 are within 15 meters of the truth position (X3, Y3) for x4597 except for a single fix solution which appeared at (X1, Y1). This single fix was of type Cell Sector resulted as a result of the phone reporting only PN 327 for that fix.

Fig. 17: Phone x4597 Fix Distribution for Tests T1, T2 and T3

Phone x0428 was positioned at truth position (X1, Y1). Regrettably, GPS fixes were enabled for this phone during the testing. The range of fixes shown in Fig. 18. indicates primarily the spread of GPS fix results since GPS solutions, when available, take precedence over any fixes based on beacon information.

The distribution of fixes for this phone is shown in Fig. 18. Since GPS was on, the GPS fixes would be attempting to position the phone at its actual position rather than at the position as modeled. The two positions are shown in the figure along with the distribution of fixes.

For the cases when the fix type was hybrid, the fix is at (X1, Y1) and due to the effect of PN327 (PB1) with a very low MAR value. Since sufficient ranging measurements were available for the solution, Whizzer was not factored. Hence, there was no distinction between the tests T1, T2 and T3.

Fig. 18: Phone x0428 Fix Distribution for Tests T1, T2 and T3

5.4.2 T1 and T4

Tests T1 and T4 can be compared to explore the influence of the sector centroid position of the pilot beacon, PB1 in this case, on the fix solution. T1 and T4 differ by the location of PB1. In T4 it is modeled to exist at the center of the tunnel, (X3, Y3), while the actual PB1 emitter is still physically located at (X1, Y1). The MAR of PB1 is also reduced to 50 meters. Note that, in the case of the tunnel test, the beacons are modeled in the BSA as emitted from omnidirectional antennas. This implies that the BSA and PDE in turn model the beacons as if they are round circles with a radius equal to the MAR.

The expectation from this comparison between T1 and T4 is to see if the position of the MS can be moved towards (X3, Y3), the center of the tunnel, and away from the center of the traffic sector. As with T1 and T2, the radiation center of the Whizzer sector is modeled in test T4 as being at the end of the tunnel at (X1, Y1).

Phone x1396 was positioned at truth position (X2, Y2). For this phone, we see in Fig. 19, that there was no change in the fixes under the conditions of T4 as compared to T1. This is to be expected since the phone x1396 positioned at (X2, Y2) will not be able to hear the beacon PB1 which was physically positioned at the other end of the tunnel (X1, Y1). The test environment was configured to make sure that PB1 would not be heard by phones beyond the mid-point.

Phone x0428 was positioned at truth position (X1, Y1). The results for x0428, as shown in Fig. 19, reveal that the Hybrid and MCS fixes were shifted towards the radiation center for PB1 at (X3, Y3). The amount of the shift is a function of the relative sizes of the MAR values for Whizzer and PB1.

Note that there is a single GPS fix for x0428 to the northeast of (X1, Y1). This point is approximately 26 meters from (X1, Y1). Note that this fix is the only pure GPS fix out of the set of approximately 120 T4 fixes. As discussed earlier, and shown in Fig. 15, the true position of the phone is just south of the position given by the GPS fix.

Fig. 19: Phone x0428 and Phone x1396 Fix Distribution for Tests T1 and T4

Phone x4597 was positioned at truth position (X3, Y3) and the resulting fix distribution is shown in Fig. 20. At the outset, it might be surprising that when the BSA entry for PB1 was shifted to (X3, Y3) the fixes moved towards (X1, Y1). Under closer examination this makes sense. When the PDE tries to estimate the position of the MS, if the MS is to be positioned at (X3, Y3) the expectation is that the delay in receiving signals from PB1 will be proportionately low. Since the beacon was actually at (X1, Y1) the measured delay was greater. So the PDE pushed the fixes away from (X3, Y3) in order for the solution to agree with the measured delay of PN 327.

There were two exceptions to the above observations. There are two outlier fixes shown as a single red fix at (X1, Y1). In reality there are two fixes located at (X1, Y1) in Fig. 20, one from test set T1 and one from test set T4. They were the only Cell Sector solution out of the entire set of tests T1 and T4. In these tests, the phone reported only Whizzer.

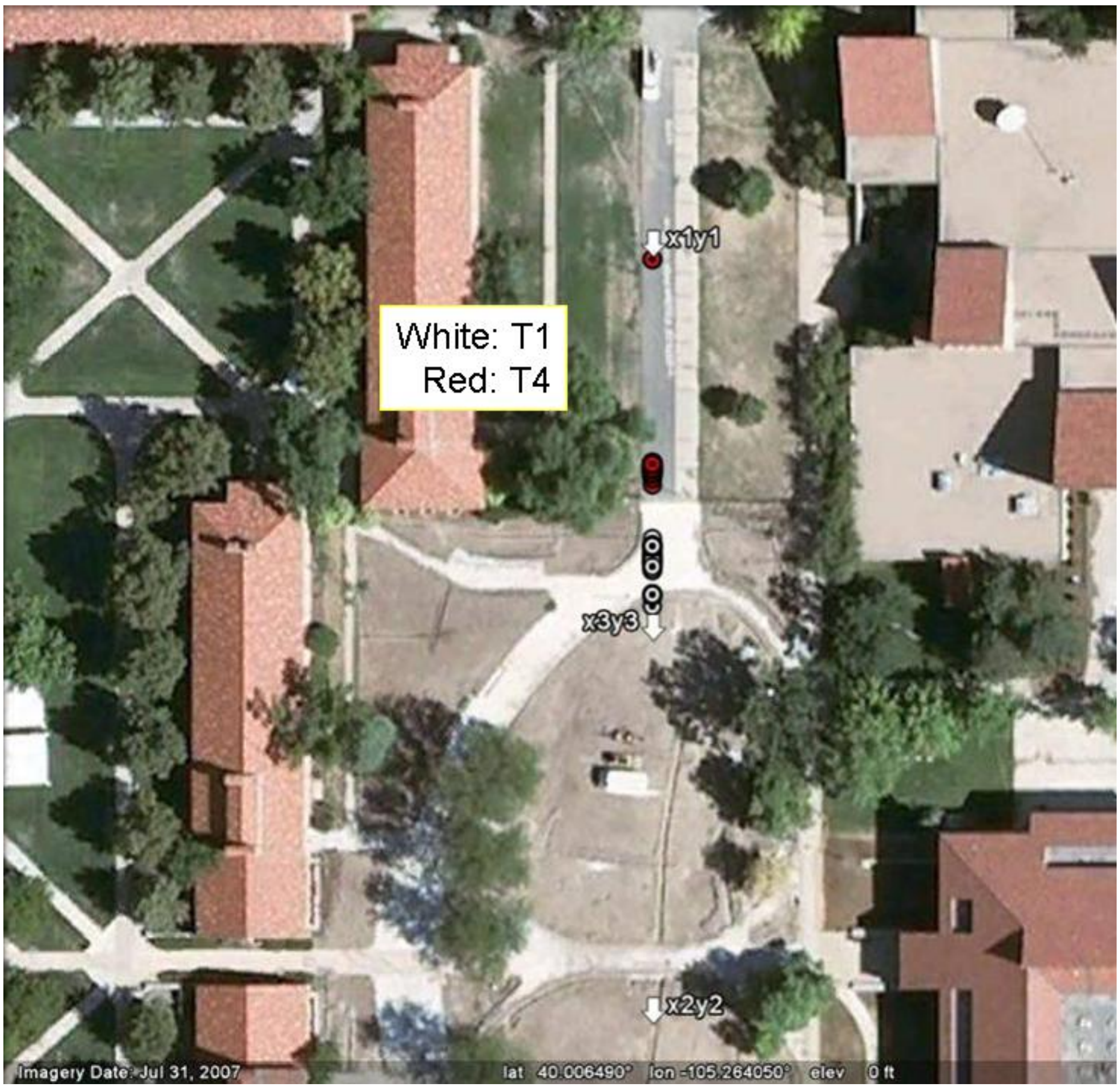

Fig. 20: Phone x4597 Fix Distribution for Tests T1 and T4

5.4.3 T4 and T5

Both test set T4 and T5 model the radiation center of PB1 at the center of the tunnel, (X3, Y3). The actual physical location of the radiation center for PB1 (PN327) remains at location (X1, Y1). The radiation center for the traffic sector, Whizzer, remains at (X1, Y1). The difference between T4 and T5 is that the MAR value for Whizzer is 100 meters for T4 and 1000 meters for T5.

The fixes for T4 should be closer to (X1, Y1) as compared to T5. This would be due to the fact that the "weight" of the MAR for a pilot used in a fix is proportional to the inverse of the MAR, not the MAR directly. Thus, the weight of 1/100 relative to 1/50 is stronger than the weight of 1/1000 to 1/50.

Phone x1396 was positioned at truth position (X2, Y2). Since Whizzer had the in-building flag set, Whizzer was not used directly in any of the fixes. The influence of the ratio of the MAR values is shown most strongly with this phone location, as shown in Fig. 21. While the effect is also observed for phone x4597, the pull is not as dramatic. The pull is offset by the fact that PB1 is configured in the BSA to be at (X3, Y3) while it is physically located at (X1, Y1).

Phone x4597 was positioned at truth position (X3, Y3). Since Whizzer had the in-building flag set, Whizzer was not used directly in any of the fixes. The fix type for x4597 was of type Mixed Mode, with both PB1 (PN327) and PB2 (PN510) being reported along with Whizzer. As noted above, the trend for T4 to move toward (X1, Y1) was observed but not as strongly as for the phone at (X2, Y2).

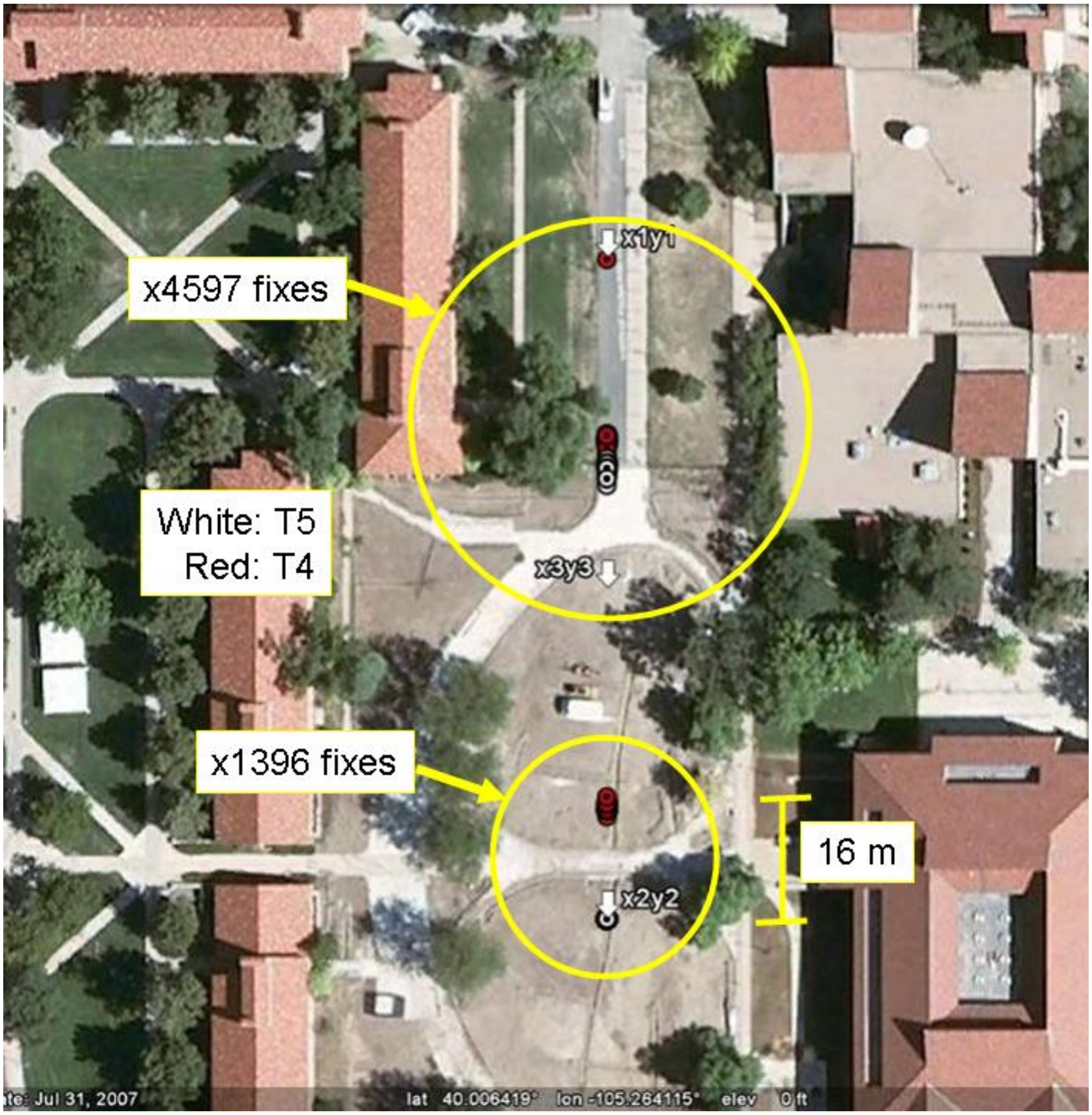

Fig. 21: Phone x1396 and x4597 Fix Distribution for Tests T4 and T5

Phone x0428 was positioned at truth position (X1, Y1). Regrettably, GPS fixes were enabled for this phone during the testing. The four fixes to the northeast of (X1, Y1) shown in Fig. 22 are GPS fix results; three from test T5 and one from test T4. Since GPS solutions, when available, take precedence over any fixes based on beacon information, they will predominate when available. They are also biased, as they should be, toward the true MS position which is 20 meters to the east of (X1, Y2). The remainder of the fixes was hybrid and Whizzer was not used in the solution since it had the in building flag set. The variation of MAR value of Whizzer therefore had no impact on the results.

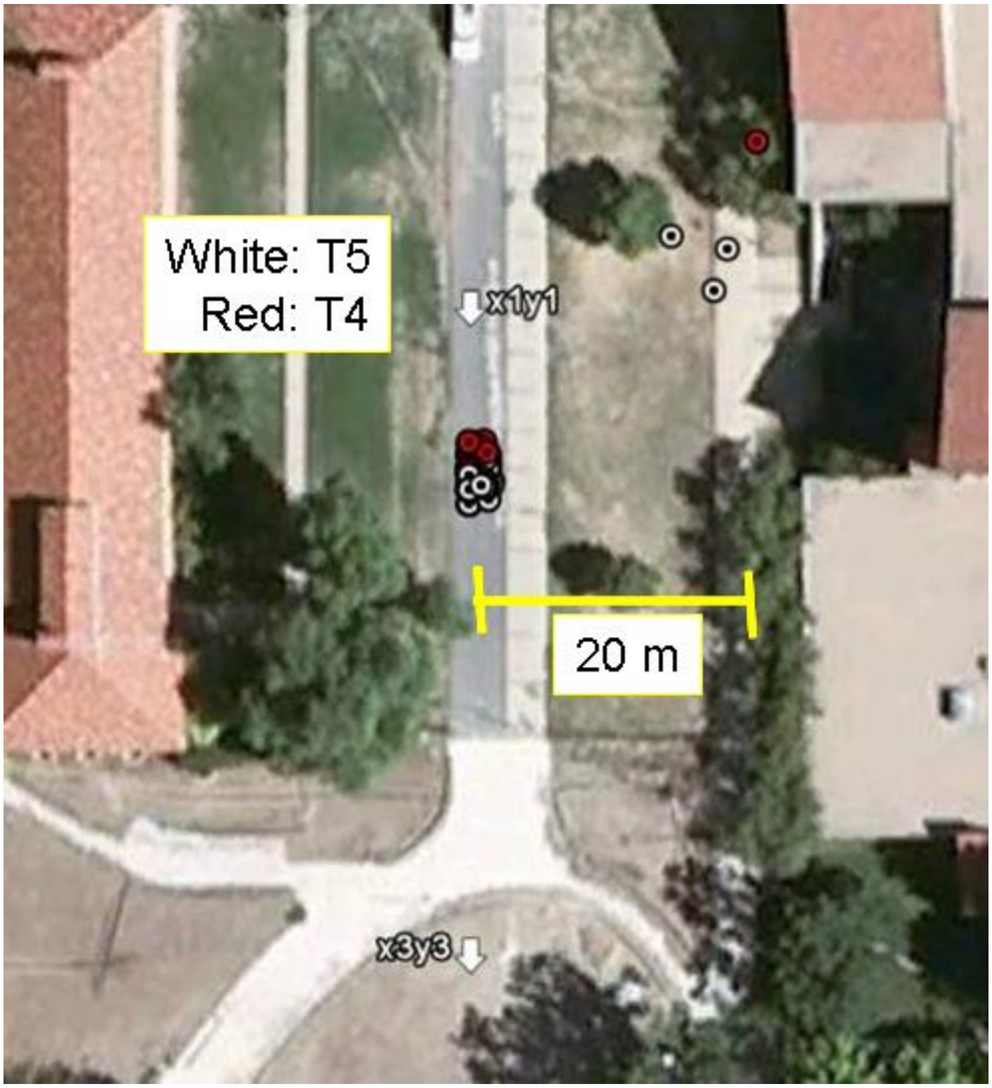

Fig. 22: Phone x0428 Fix Distribution for Tests T4 and T5

5.4.4 T4 and T6

Test configuration T6 modeled the radiation center of both PB1 and PB2 at the center of the tunnel, (X3, Y3), while still being physically located at (X1, Y1) and (X2, Y2), respectively. The MAR value for each beacon was set to 50 meters so as to include the full length of the tunnel, and thus the phones at (X1, Y1) and (X2, Y2). Please recall that the radiation center of only PB1 was modeled at the center of the tunnel (X3, Y3) for test T4. These tests would affect x1396 and x4597 at (X1, Y1) and (X2, Y2) since only those locations can hear PB2. For those locations, the expectation was that in T6 the fixes for T6 would be closer to (X3, Y3) than those for T4.

Phone x1396 was positioned at truth position (X2, Y2). Since Whizzer had the in-building flag set, Whizzer was not used directly in any of the fixes. The influence of the ratio of the MAR values is shown in this comparison similar to the comparison of T4 and T5 as discussed earlier. This can be seen by comparing Fig. 21 and Fig. 23.

Phone x4597 was positioned at truth position (X3, Y3). Since Whizzer had the in-building flag set, Whizzer was not used directly in any of the fixes. The fix type for x4597 was of type Mixed Mode, with both PB1 (PN327) and PB2 (PN510) being reported along with Whizzer. Since, in T6, PB2 is now modeled as being located at (X3, Y3) we see, in Fig. 23, the expected result that the solutions are pulled toward (X3, Y3) as compared to T4.The single outlier fix from test set T4 shown at (X1, Y1) was discussed in the previous section.

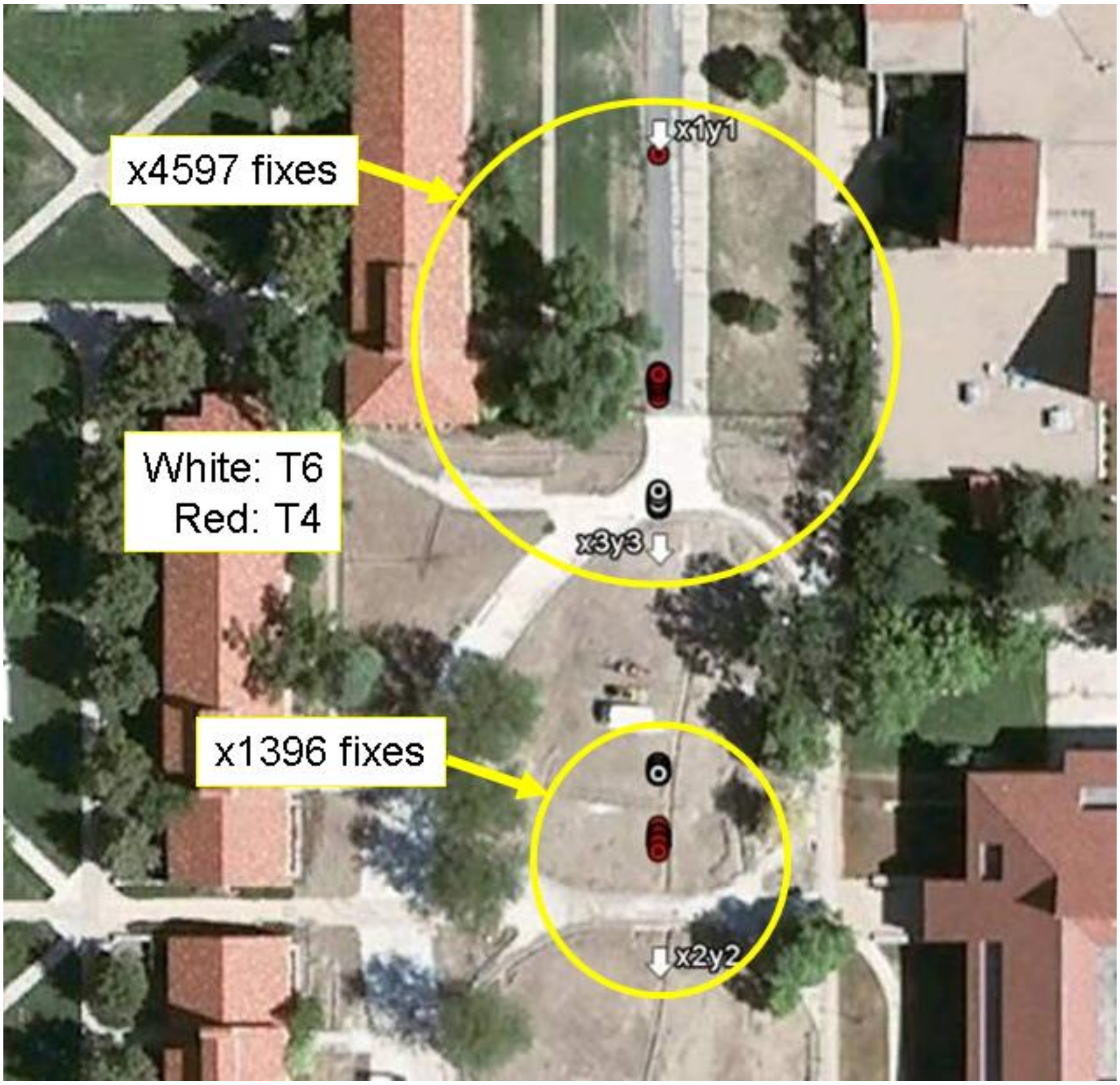

Fig. 23: Phone x1396 and x4597 Fix Distribution for Tests T4 and T6

Phone x0428 was positioned at truth position (X1, Y1). Regrettably, GPS fixes were enabled for this phone during the testing of (X1, Y1). Nevertheless, T4 and T6 are identical with respect to position (X3, Y3).

Fig. 24: Phone x0428 Fix Distribution for Tests T4 and T6

5.5 Results – Tunnel Served By an External Sector

Test sets T7 through T9a represent the case where the tunnel is covered by a cell/sector external to the tunnel that also serves MS external to the tunnel. In other words, it is not practical to model the radiation center of the sector as being in the middle of the tunnel. To do so would corrupt the position determination solutions for all of those users that are external to the tunnel.

Thus for these tests the radiation center for Whizzer is modeled as it is normally found for this sector, at a position that we refer to in Table 19 as (a,b) which is approximately 368 meters to the westnorthwest (bearing: approximately 290 degrees) of the (X1, Y1) test location. Also the in-building flag is not set for these tests as it would be for a sector that serves users above ground.

5.5.1 T7, T8, T9

Tests T7, T8 and T9 varied the MAR value of the pilot beacons but Whizzer was kept constant with a MAR of 2700 at its original antenna center without the in-building flag. It was observed that this setup was unusable for positioning since all the fix solutions were at Whizzer irrespective of the test location, as shown in Fig. 25. The only exception to this rule was the fixes for Phone x0428 with GPS on. Closer inspection revealed that the pilot beacons were failing the initial PN validation process. Validation is the phase when a reported pilot's physical location is looked up in the BSA and compared with the reference PN (Whizzer 273). The PDE starts with the reference PN and compares the other reported phase measurements to the reference PN to see if the phase or TDoA estimate is feasible for a given combination of antenna location and MAR value of the pilot beacon as configured in the BSA. The repeater and DAS setup added so much additional delay (additional delay implies the phone is farther away from Whizzer) to the phase measurement of Whizzer that the PDE determined that there was no way additional measurements of the pilot beacons located at (X1, Y1) and (X2, Y2) could be heard simultaneously. This internal check by the PDE is a safety measure to prevent misconfigured entries in the BSA from distorting the final solution. These results are problematic for the implementation of pilot beacons for cells that cover both an indoor and outdoor environment.

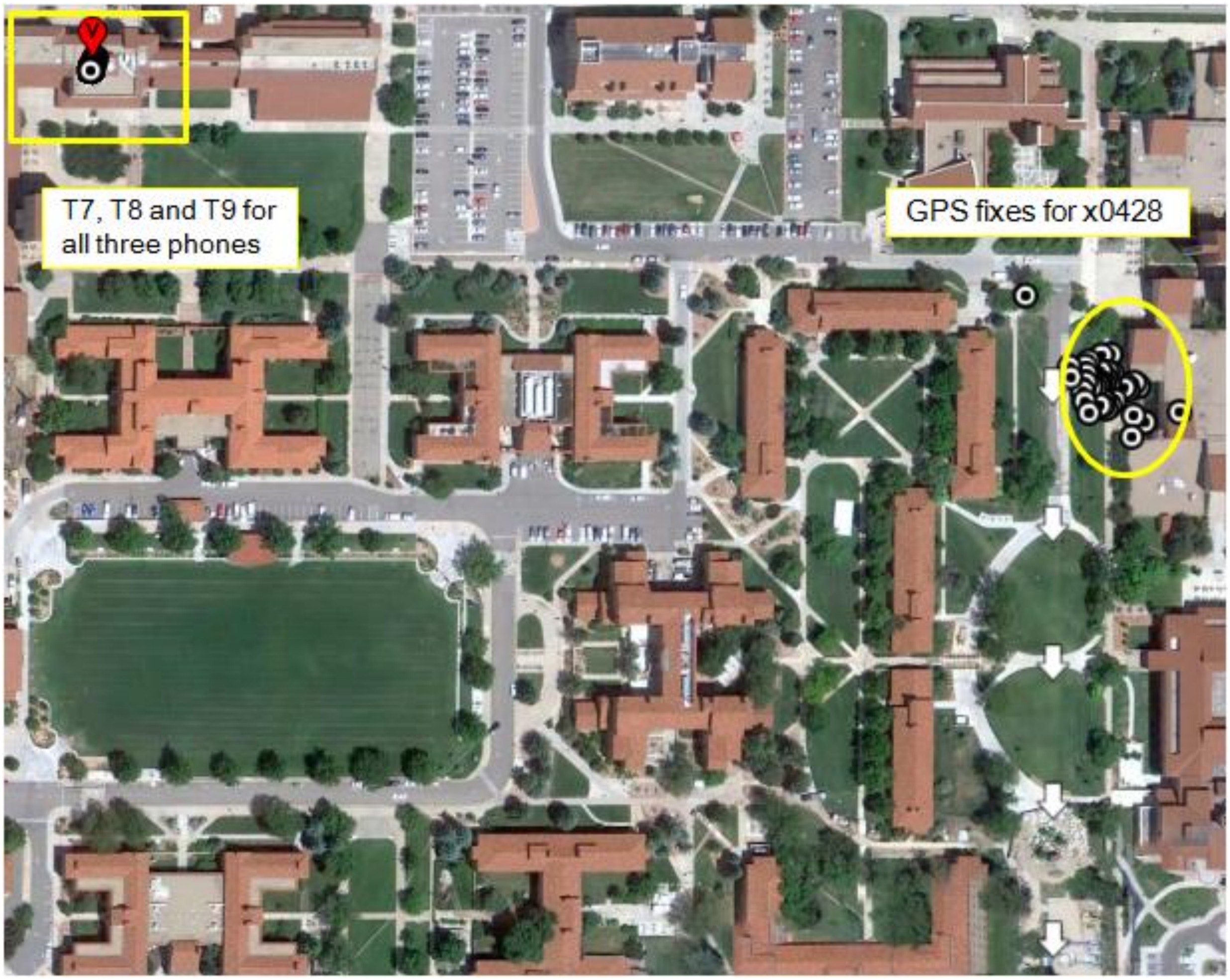

Fig. 25: All Phones, Fix Distribution for Tests T7, T8 and T9

5.5.2 T7a, T7b and T9a

These additional tests were added to the test plan to see if the problem could be mitigated. In tests T7a and T7b the beacons were marked as in-building to prevent their ranging measurements from being used in the solution. Users could be positioned in the tunnel only if the MAR value of the two beacons were relaxed to model a larger coverage radius (T9a).

5.5.2.1 T7a

Phone x1396 was located at truth position (X2, Y2). Since Whizzer did not have the in-building flag set, it was used directly in the fixes in set T7a. All of the fixes for set T7a fail to lookup PN 510.

Although the in-building flag precludes the PN from being used in ranging it is apparent that a PN failing lookup is not used in any kind of a solution. Thus, all of the T7a fixes were Mixed Cell Sector using just Whizzer. The solutions were at the Whizzer site resulting in an error of approximately 413 meters.

Phone x0428 was positioned at truth position (X1, Y1). The pattern described above for phone x1396 also occurs for x0428 except that PN 327 (PB1) failed lookup in the place of PN 510. The error from truth under the conditions of T7a is approximately 368 meters.

Phone x4597 was positioned at truth position (X3, Y3). Since Whizzer did not have in-building flag set, Whizzer was used directly in the fixes. All of the fixes for set T7a report the same three PN offsets (273, 510, 327) except that PN 510 failed lookup but PN 327 passed lookup. Therefore, pilot 327 was used in the fixes. The resulting solutions were of the type Mixed Cell Sector utilizing 273 and 327 with the small MAR of PN327 drawing all the fixes to (X1, Y1) as shown in Fig. 26.

Fig. 26: Phone x4597 Fix Distribution for Tests T1 and T7a

5.5.2.2 T7b

Since Whizzer had the in-building flag set, it was not used for ranging. Now, none of the pilots failed lookup. Phone x1396 was located at truth position (X2, Y2) and Phone x0428 was located at truth position (X1, Y1). With the in-building flag set for all pilots, they were used to compute a Mixed Cell Sector solution. At these two truth locations only one beacon was heard and it dominated the solution, dragging all the fixes towards it. This Phone x0428 was positioned at (X1, Y1) and Phone x1396 was positioned at (X2, Y2). For Phone x4597 the logic is similar but since it reported both beacons with small MARs the Mixed cell Sector solution had to give equal importance to both the beacons, resulting in solutions that were midway between (X1, Y1) and (X2, Y2) at (X3, Y3). The fix distribution for all the test locations is shown in Fig. 27.

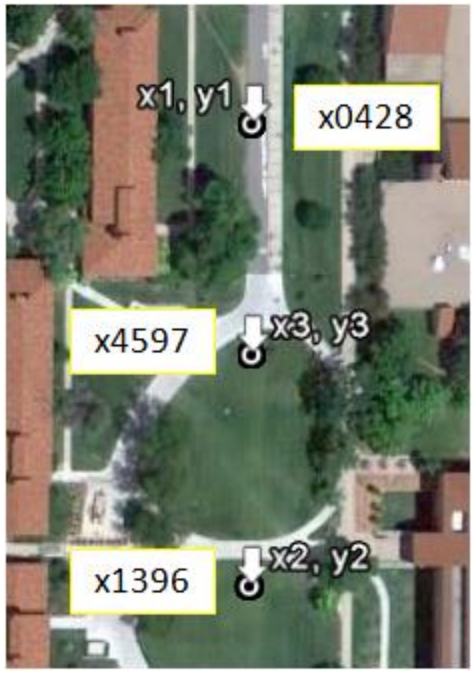

Fig. 27: All Phones, Fix Distribution for Tests T7b

5.5.2.3 T9a

In test T9a, an alternate approach was taken to fix the failing lookup process by relaxing the beacon MAR values from 50 meters to 300 meters to model a greater coverage. This relaxation did not yield the desired results entirely. For phones x1396 and x0428 at (X2, Y2) and (X1, Y1), respectively, the two beacons still failed the validation check. On the other hand, for measurements by phone x4597 at (X3, Y3) beacon 510 which was failing lookup in test T7a passed validation, with the validation check resulting in a shifting of the solution from (X1, Y1) in T7a to (X3, Y3) indicating that both PN 327 and PN 510 contributed to the fix process as shown in Fig. 28.

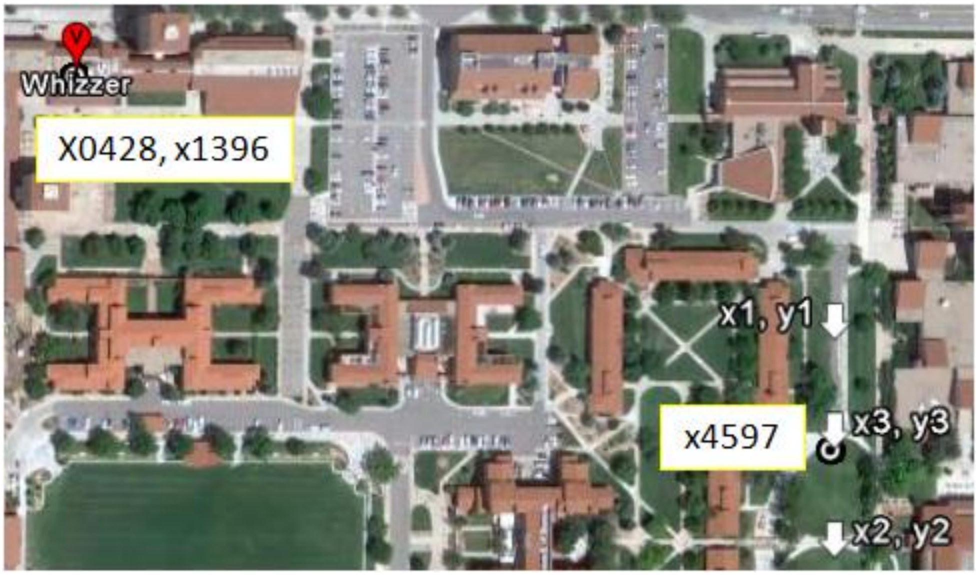

Fig. 28: All Phones, Fix Distribution for Tests T9a

5.6 Extended Tunnel Tests

In order to explore the ability of pilot beacons to position users in a tunnel who were far from the beacon, the equipment and the truth positions were reconfigured as shown in Fig. 29.

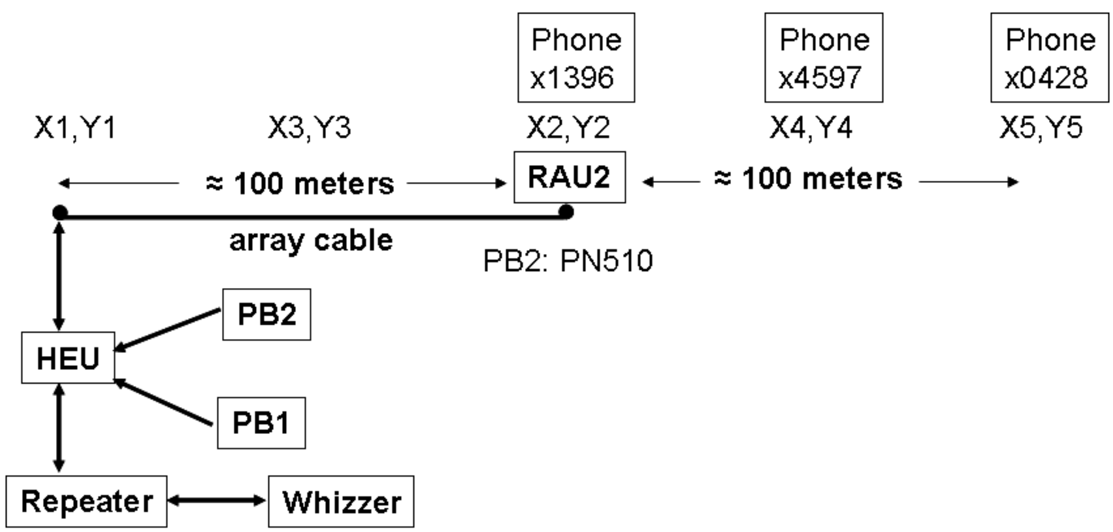

Fig. 29: Equipment configuration for Extended Tunnel Tests

The equipment was essentially the same as in the previous tests. The difference was that PB1 was not used and left off. It would not be heard by the test phones in their new locations. The second modification was that new truth positions were defined as (X4, Y4) and (X5, Y5). These truth positions were further down the tunnel with (X4, Y4) being 50 meters from (X2, Y2) and (X5, Y5) being 100 meters from (X2, Y2). The phones were assigned to the positions shown in Fig. 29.

Three tests in this extended tunnel configuration were performed as shown in Table 14. The primary change was to move the modeled location of PB2 from its actual physical location to a point that was further down the tunnel (X4, Y4) and then to a point that was fully down the tunnel (X5, Y5). In all cases the actual location of the radiator for PB2 remained at (X2, Y2). Note that the radiation center for Whizzer 273 was held constant at (X1, Y1). The in-building flag was set for Whizzer 273 so that it was not used for ranging fixes.

Table 14: Extended tunnel tests

Test	**Antenna Center**		**MAR**	
	PB2 PN510	**Whizzer (Traffic)**	**PB2**	**Whizzer (Traffic)**
TE1	X2, Y2	X1,Y1	100	200
TE1a	X4, Y4	X1,Y1	100	200
TE1b	X5, Y5	X1,Y1	100	200

5.7 Extended Test Results

5.7.1 TE1, TE1a and TE1b

The expected performance for these tests is for a Mixed Cell Sector solution for all tests. The solution is expected to follow the modeled radiation center for PB2 from (X2, Y2) to (X4, Y4) to (X5, Y5) for TE1 to TE1a to TE1b, respectively.

Phone x1396 was positioned at truth position (X2, Y2). Since Whizzer had the in-building flag set, Whizzer was not used directly in the fixes. All of the fixes were of type MCS as expected. As shown in Fig. 30, the solutions for x1396 followed the modeled locations for PB2 as expected.

Phone x4597 was positioned at truth position (X4, Y4). Since Whizzer had the in-building flag set, Whizzer was not used directly in the fixes. All of the fixes were of type MCS as expected. As shown in Fig. 30, the solutions for x4597 followed the modeled locations for PB2 as expected.

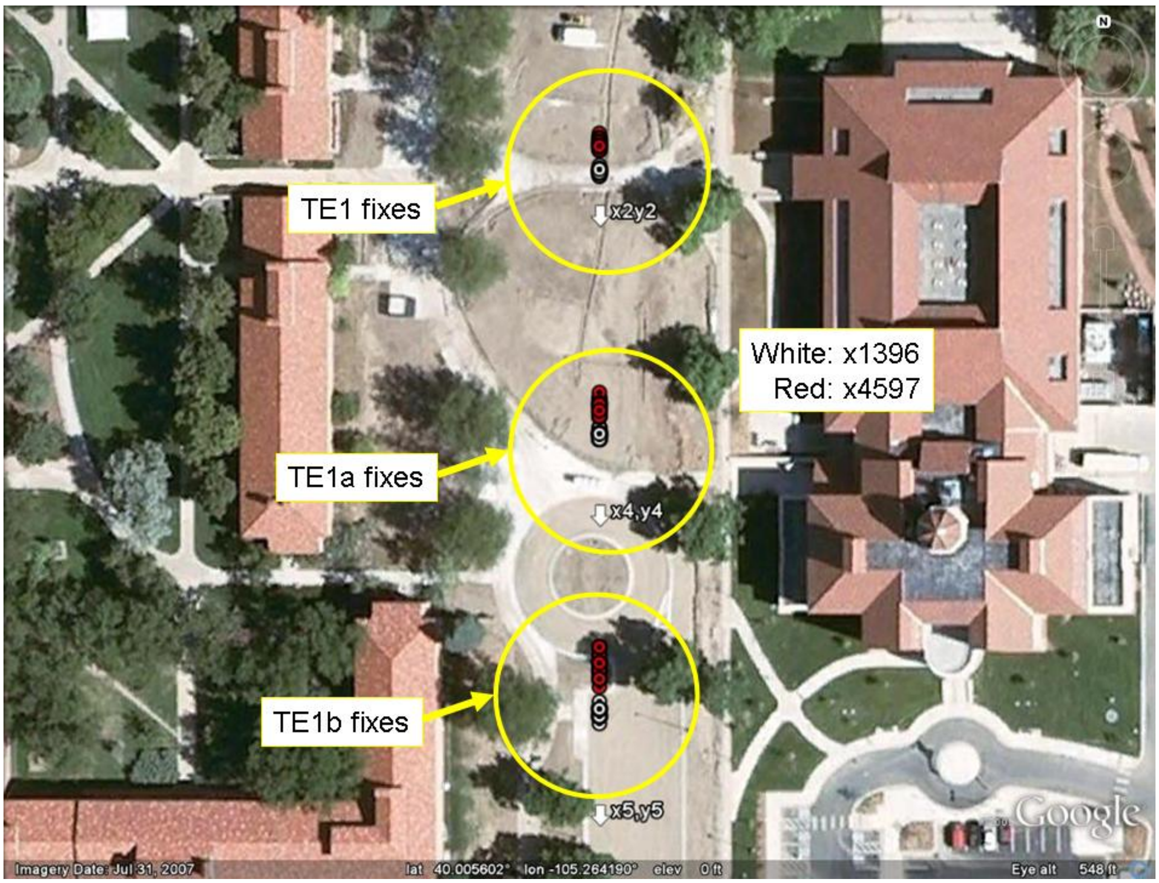

Fig. 30: Phone x1396 and x4597 Fix Distribution for tests TE1, TE1a and TE1b

It should be noted how Whizzer 273 still affects the final solution set by adding a bias toward (X1, Y1) The bias is greater for x4597 which was physically farther from (X1, Y1).

Phone x0428 was positioned at truth position (X5, Y5). The range of fixes is shown in Fig. 31 for test sets TE1, TE1a and TE1b. All of the fix types were Mixed Cell Sector. The variability in the fixes is believed to be the result of weak signal from PB2. Phone x0428 was the farthest from PB2, physically located at (X2, Y2). The resulting fix distribution is shown in Fig. 31. While the results were noisy, the trend followed the expected pattern of following the modeled radiation center for PB2 from (X2, Y2) to (X4, Y4) to (X5, Y5) for TE1 to TE1a to TE1b, respectively.

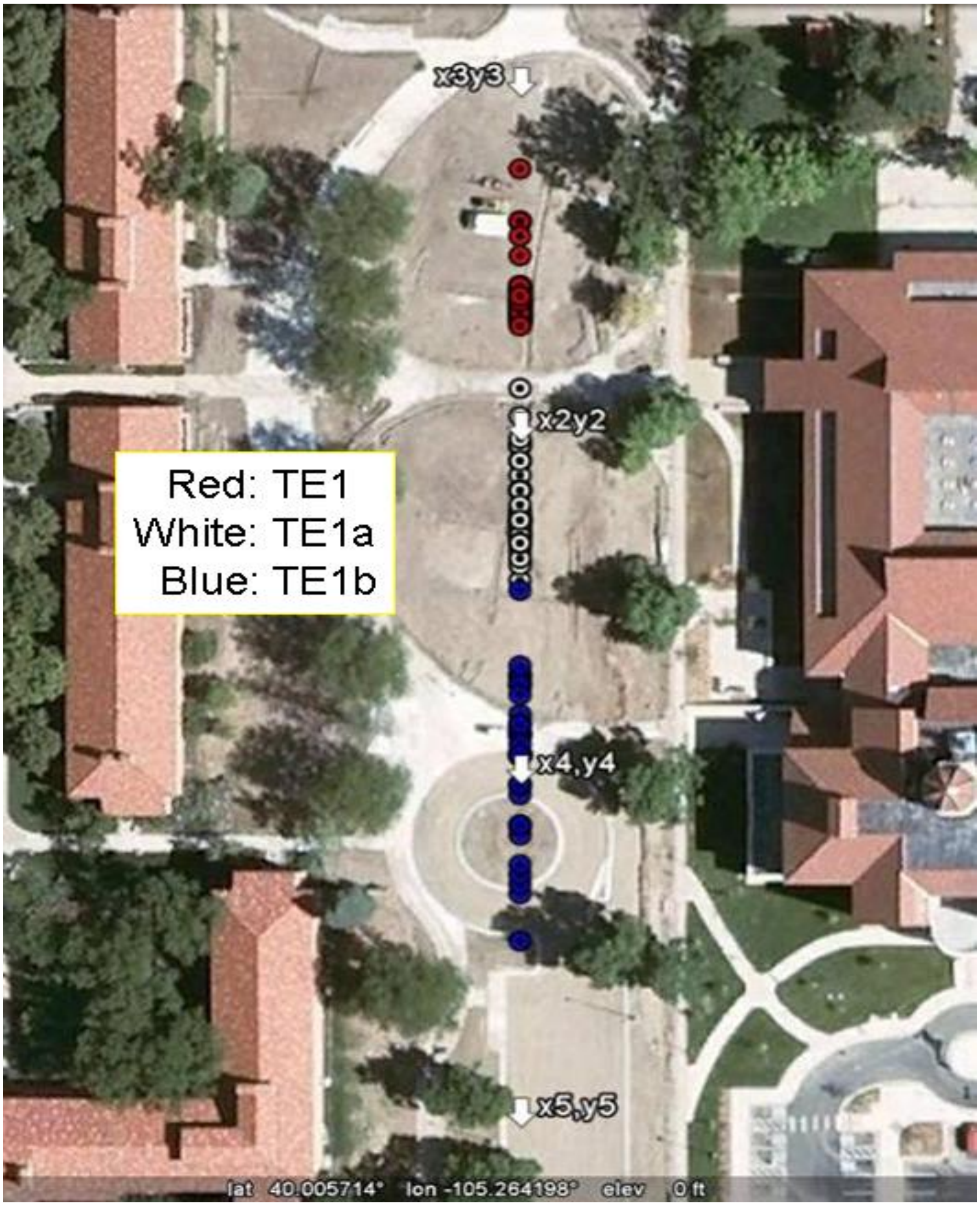

Fig. 31: Phone x0428 Fix Distribution for tests TE1, TE1a and TE1b

The pilot beacon concept was useful for all cases configured to simulate situations where the serving sector was dedicated to the tunnel and failed for most of the cases when the serving sector had a macro footprint and was also repeated into the tunnel.

CHAPTER 6

Arena Environment using Indoor Beacons

6.1 Introduction

An arena poses a very common design challenge for network engineers trying to provide good quality of service. These buildings have a high user density compared to other sites and often require a repeater or a dedicated base station to provide complete coverage. Stadiums and conference centers are similar buildings that often need similar attention. Accurately positioning users in such venues adds another layer of complexity to the network. The fundamental question when considering augmentation of the network with pilot beacons is whether significant improvements in position accuracy can be achieved by using dedicated indoor beacons to serve the arena.

A distinction must be drawn between the dedicated base station and the repeater based deployment cases. If the arena is supported by only a dedicated BTS, Cell Sector solution will locate the user to the building covered by the DAS. For this circumstance, the radiation center defined in the BSA should be the center of the arena and the MAR value should be set to the arena radius. By comparison, simulcasting traffic service into an arena using a repeater (sometimes also known as Bi-Directional Amplifier, BDA) and a DAS precludes using the traffic pilot for ranging. This is because the serving traffic sector must maintain the outdoor radiation center in the BSA for the benefit of users outside of the arena. In this case, the in-building flag should be set in the BSA. In other words, the repeater fed system implies that the sector is used elsewhere in the macro network and its location and FLC values in the BSA cannot be altered to suit the arena deployment.

Although the repeater and dedicated base station discussion is also presented in Chapter 5 on tunnels, a distinguishing feature of the arena deployment is the fact that there is a greater probability of receiving weak GPS signals and other BTS signals that may be sufficiently strong to produce AFLT or hybrid solutions. Moreover, these additional signals may or may not pass through the repeater/DAS system resulting in additional confusion for the PDE due to different delay paths. Therefore, under many circumstances venues fed by a repeater are prone to position accuracy errors.

The objective of testing in this venue was to answer the following three questions:

1. What are typical solution accuracies when a specific donor accompanied by other macro network signals is repeated into this kind of a venue for distribution via a DAS?
2. What are the effects of adding beacons to the various potential environments above?
3. What impact would beacons have on a solution with a dedicated in-building base station?

6.2 Arena Set-Up and Configuration

The Coors Events Center, a medium-sized collegiate basketball arena with a seating capacity of over 11,000 was chosen for testing. It is located just southeast of the locations used for truth positions in the outdoor beacon tests. The location of the arena relative to the sector used to provide cellular network connectivity, Whizzer, is shown in Fig. 32.

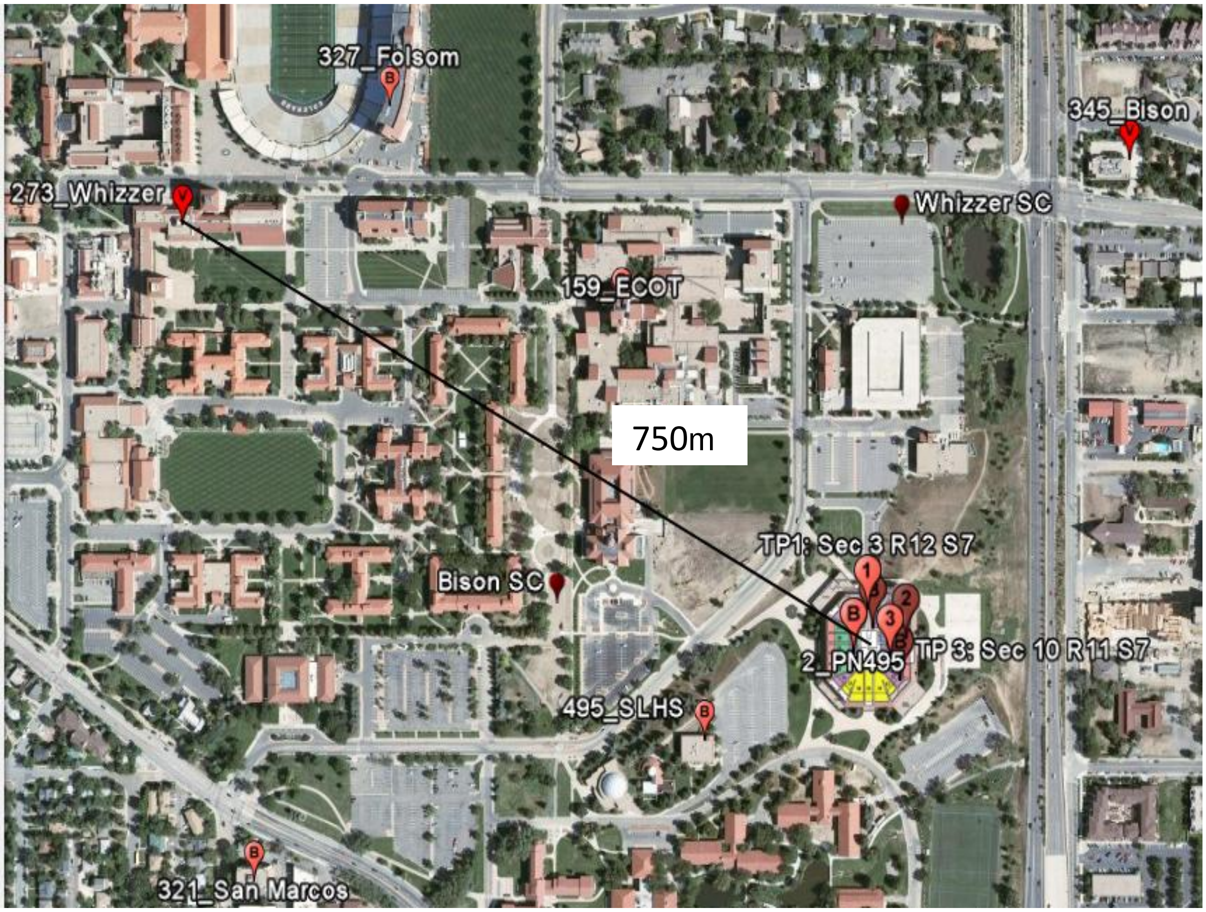

Fig. 32: Arena location showing distance from Whizzer

An indoor fiber optic DAS system, same as the one used in the tunnel deployment was installed in the arena for deploying the traffic and the pilot signals inside the arena. The equipment for the test was deployed in three locations within the arena. First, there was a temporary set of GPS antennas and one tripod-mounted Yagi-Uda antenna placed on the roof of the arena. The actual equipment was kept inside the arena high above the arena floor on the catwalks that are used to service the flood lights in the arena. This equipment consisted of three pilot Beacon units, and three Corning DAS Head End Units (HEUs), CSI Bi-Directional Amplifier (BDA). Lastly, there was a set of three “Remote Antenna Units” (RAUs) along with the associated service antennas placed in the arena at locations marked by the symbol “B” in Fig. 33.

The function of the installed equipment was to re-radiate the Verizon serving sector cellular signal (Whizzer, sector 273) along with other external macro network signals. The DAS equipment distributed all the macro signals and the three beacon signals into the arena. In addition, one each of the three pilot beacon signals was radiated from the radiating antenna locations inside the arena. The placement of the antennas and beacons inside the arena is shown in Fig. 33. The signal from PB2 (PN495) radiated only from the second RAU and PB3 (PN510) only from the third RAU. A deployment approach based on adding sectors for coverage would have involved placing the three beacons with highly directional antennas at the center of the arena facing towards the stands as pointed by the red arrows. Instead, this configuration was optimized for the deployment of pilot beacons by maximizing (as much as possible on the catwalk) the separation between the individual beacon locations.

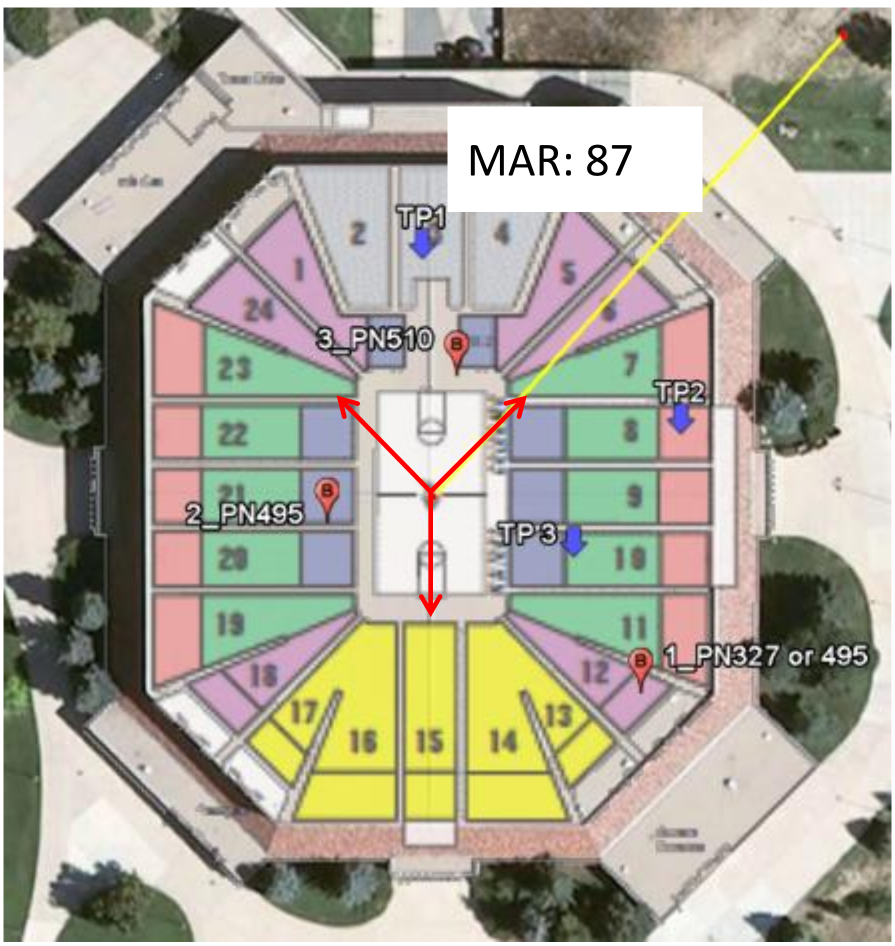

Fig. 33: Arena Configuration Showing Truth Positions (TP) and Antenna Locations (B)

Fig. 34 shows the various delays in the RF path. The network positioning system is designed to measure times of arrival of pilot signals and uses the information to generate trilateration solutions. Additional (artificial) delays beyond LOS propagation distort those solutions. There are two sources of delay in this circumstance: the repeater and the DAS system. The repeater (BDA) delay of the equipment was specified to be approximately 2.5 µs. In addition, each RAU had a different delay based on the length of the fiber from the HEU as shown in Fig. 34. Finally, there was also delay from the Whizzer 273 radiation center to the BDA at the event center. This delay was approximately 2.52 µs.

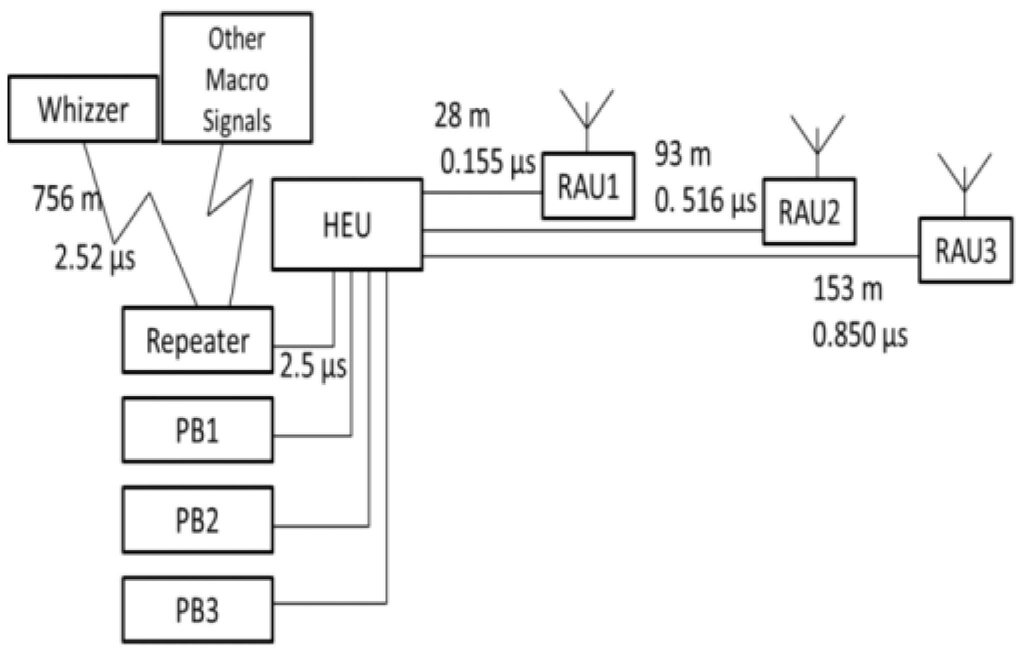

Fig. 34: Equipment Configuration showing delays in the system for Arena testing

The beacon configuration used for the tests is shown in the table below.

Table 15: Beacon configuration for arena tests

Parameter	Value
Channels Used	1
Transmit Power	+ 6 to 10 dBm (Indoor Beacons) +19 dBm (Outdoor beacons)

Parameter	Value
Transmit Channel	Channel 630 (889.6 MHz)
PN Offset	One per beacon: 159, 321, 327, 495, 510
Tau Offset	Values as determined by FLC

6.3 Arena Tests

With the equipment deployed as per Fig. 33 and Fig. 34, tests cases were executed as shown in Table 16. The MAR values are given in units of meters. Note that these were only a subset of the originally intended tests. Due to the failure of multiple indoor beacons on the days allocated for testing, testing was discontinued.

The ECOT (PN159) and Folsom (PN321) were outdoor pilot beacons used to simulate PN sources from a typical repeated macro environment. The “Whizzer Location” column indicates the location of the radiation center that was entered into the BSA for Whizzer. The location (a, b) was the position outside of the arena that Whizzer normally used to accommodate the outdoor traffic while (x, y) is the arena center. The “Whizzer IB flag” column indicates whether the in-building flag was set for Whizzer. This affects the way the PDE uses information about Whizzer’s location when it is reported in a fix. The IB flag excludes the particular PN offset from being used for ranging calculations.

During these tests, three test phones were placed at locations as shown in Fig. 33 using the blue downward arrow symbol along with the text identifier “TP” to indicate truth position. The phones with numbers ending in x0428, x1396 and x4597 were placed at locations TP1, TP2 and TP3 respectively. Each test was conducted by initiating approximately 120 position fix requests from each phone (simultaneously) using the Rover application on the phone.

Table 16: Arena Tests

Test Set	Outdoor ECOT	Outdoor Folsom	Whizzer Location	Whizzer IB Flag	Coors PB1	Coors PB2	Coors PB3	GPS
T1	ON	ON	A, B	None				ON
T2	ON	ON	A, B	None				OFF
T3	ON	ON	A, B	None	87	87	87	ON
T4	ON	ON	A, B	None	87	87	87	OFF
T5	OFF	ON	A, B	None			87	OFF
T6	OFF	ON	A, B	None	87		87	OFF
T7	OFF	OFF	A, B	None			87	OFF

6.4 Arena Test Results

6.4.1 T1, T2

Tests T1 and T2 explore the effectiveness of using unenhanced positioning inside the arena. Due to weak GPS signals indoors and possible phase ambiguity due to multipath, GPS fixes are not expected to deliver good accuracies all the time. T1 has GPS ON generating a mix of GPS, Hybrid and AFLT solutions. T2 has GPS OFF, generating AFLT solutions. All indoor beacons are turned off for both the tests.

It was observed that there were no phone-specific variations in the fixes (in both T1 and T2) and it would be sufficient to discuss results of the test as a whole. A scatter plot of the results for tests T1 and T2 is shown in Fig. 35. For generating GPS fixes, it is necessary to generate a pre-fix solution as discussed in Chapter 2. Due to the presence of sufficient pilots, AFLT/Mixed Mode prefixes were generated. Since the in-building flag was not set for the repeated Whizzer signal, it led to errors in the fixes for AFLT and Mixed Mode fix types. The PDE computed the fix location assuming the reported signal levels were directly from the Whizzer without accounting for the fact that at the arena, the signal levels were artificially boosted by the repeater. Results from T2 consist of only AFLT/Mixed Mode fixes from T1 (fixes inside the rectangle). The PDE computed the fix location assuming the reported signal timing were directly from the RF sources without accounting for the latencies introduced by the repeater and DAS in the arena.

GPS solutions were computed based on the location predicted by the pre-fix operation. These final solutions were spread around the neighborhood of the truth positions as shown in Fig. 35. The only difference between T1 and T2 is that the GPS was turned off in T2. Thus, all the fixes were AFLT/Mixed Mode in T2 and distorted by delays as mentioned above.

It is thus evident that when a sector is shared between the macro network and a separate venue fed by a repeater, unavailability of GPS signals can result in distorted position solutions for ranging fixes originating inside the location covered by a repeater. Even when GPS solutions are available for indoor users, the fix location can be outside of the venue.

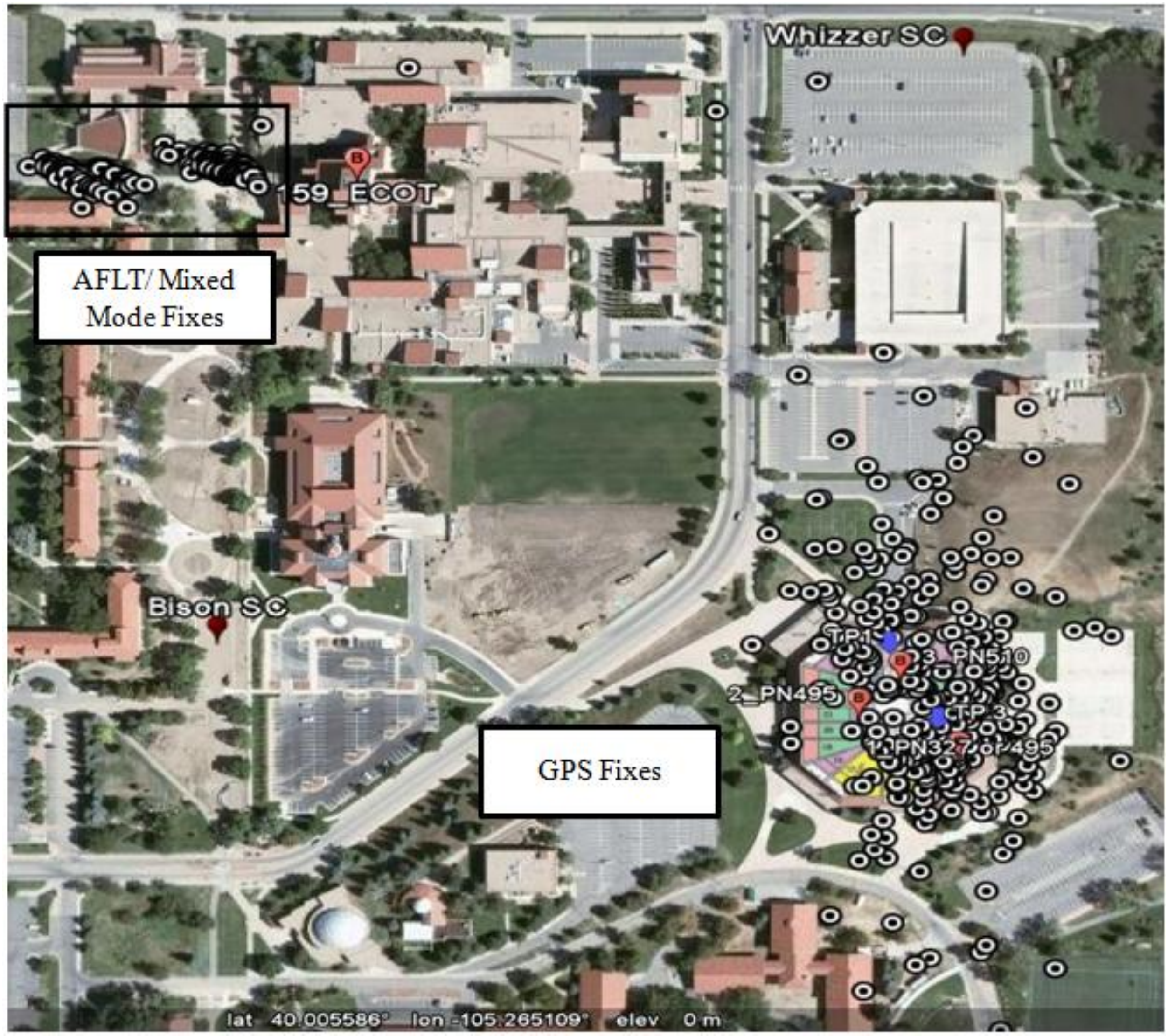

Fig. 35: Fix distribution for T1, T2 for phones at TP1, TP2 and TP3

6.4.2 T3, T4

Tests T3 and T4 explore the effectiveness of GPS and AFLT based positioning solutions generated by phones inside the arena when using indoor pilot beacon enhancement. Outdoors, GPS fixes deliver the best accuracies but GPS signals get weak indoors and are often unavailable. Both tests T3 and T4 have two outdoor beacons ON along with three indoor beacons. For the purposes of these tests, the outdoor beacons are equivalent to macro cells whose repeated signals would be heard by the indoor subscriber and used with either Hybrid or AFLT solutions. As the DAS node energy levels are low, the indoor beacons would each cover only a subset of a larger venue. However, for this venue, each pilot beacon was heard everywhere inside. Each beacon was assigned a MAR value of 87 meters, which is a little over the venue diameter.

For test set T3, phone x4597 was positioned at TP1. The fix distribution for T3 is shown in Fig. 36 below. The fixes inside the circle were prefixes used in the final GPS solution. Fixes outside the circle were final GPS fixes. The fixes were predominantly within the arena. Phones x1396 and x4597 were positioned at TP2 and TP3, respectively, with the distribution of fixes shown in Fig. 36b and Fig. 36c, respectively. The results were similar to those observed for x4597 at TP1. Fixes were predominantly within the arena for TP2 and TP3 also. Adding pilot beacons to GPS/Hybrid solutions generates circumstances where a more accurate AFLT pre-fix leads to better assisted GPS performance, pulling nearly all solutions generated inside the venue. Comparing the scatter plots in Fig. 36 to Fig. 35 illustrates the benefit of adding pilot beacons into the venue for GPS solutions as well non-GPS solutions.

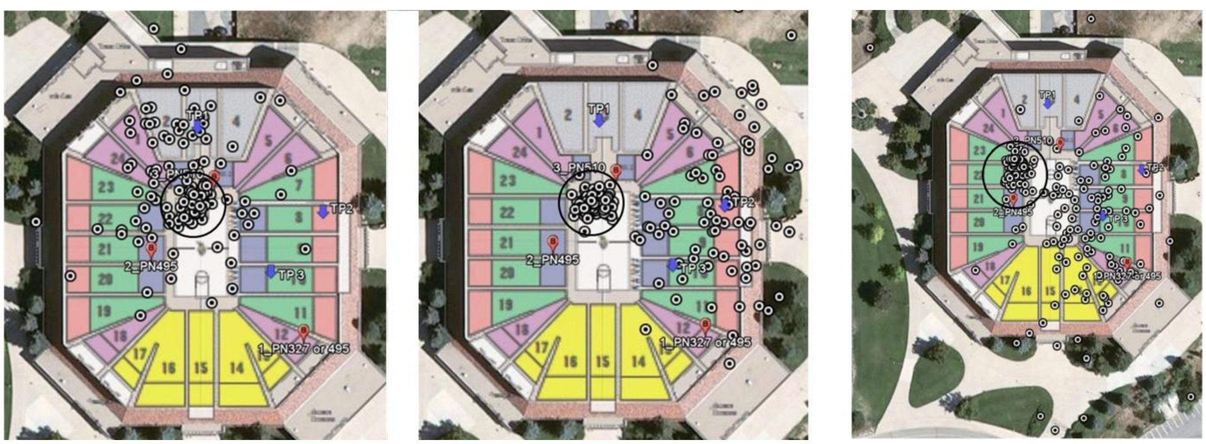

Fig. 36: Fix distribution for T3 for phones at: a. TP1, b. TP2, and c. TP3

In contrast to T3, T4 has GPS OFF. Fig. 37 shows fixes for T4 at TP1, TP2 and TP3. Pilot beacons dominate the AFLT solutions distorted due to the repeated macro network pilots and are pulled back into the arena thus helping overcome the distortion.

Fig. 37: Fix distribution for T4 for phones at: a. TP1, b. TP2, and c. TP3

Comparing the scatter plots in Fig. 37 to the AFLT solutions of Fig. 35 illustrates the benefit of adding pilot beacons for non-GPS solutions.

6.4.3 T5, T6

In T5 and T6, one of the outdoor beacons was removed, one or two of the indoor beacons was removed and GPS was off. It is observed from Fig. 38 that although the fixes were of type AFLT, with Whizzer and Folsom contributing to the fix, the variation of the fix location is only due to the indoor beacons (smaller MAR).

In T5 only PB3 is ON, along with Whizzer and one outdoor macro signal. Since PB3 has a MAR value that is much smaller in comparison, the AFLT solutions cluster around the beacon irrespective of the truth position. When PB1 is also turned ON, there are two sources with small MARs and fixes are distributed along the line connecting the two beacons. Fixes from TP3 was closer to PB1 along the line segment. On the other hand, fixes from TP1 which was closer to PB3 were closer to PB3 on the line segment.

It is observed that distortions in AFLT due to repeated macro signals can be overcome by introducing just one indoor beacon in the AFLT solution. However, greater resolutions are not possible with just one beacon. A slightly greater resolution and better accuracies are achieved by using two beacons. Although this trend was not carried into the specific three-beacon configuration in T4, optimizing the beacon configuration could lead to better results as was observed in the tunnel testing.

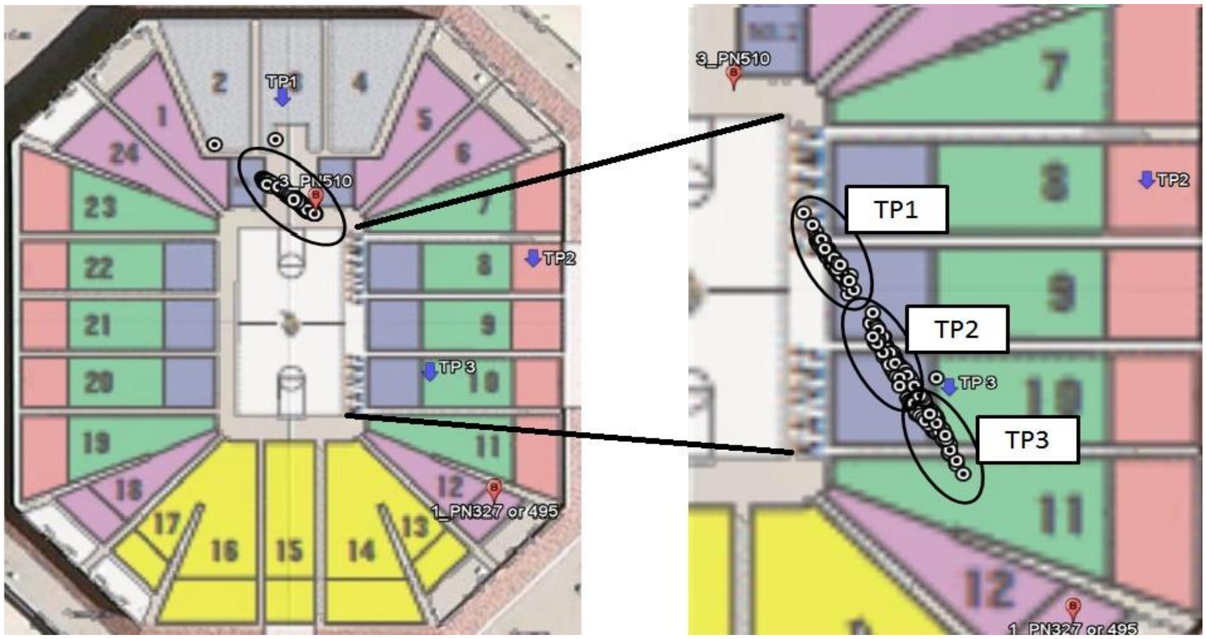

Fig. 38: a. Fix distribution for T5, b. Fix results for T6

6.4.4. T7, T8, T9

In T7, the only signal entering the venue from the macro network is Whizzer. Without pilot beacon deployment in the venue, the in-building subscribers would only generate a Mixed Cell Sector/Cell Sector solution at the center of the arena. The PDE uses round trip delay measurements to define the distance from the BTS or signal origin. However, repeater and DAS delays distort this measurement significantly and errors increase.

By adding just a single pilot beacon, all solutions become Mixed Mode or Mixed Cell Sector and are pulled inside the MAR value of the active beacon as shown in Fig. 39.

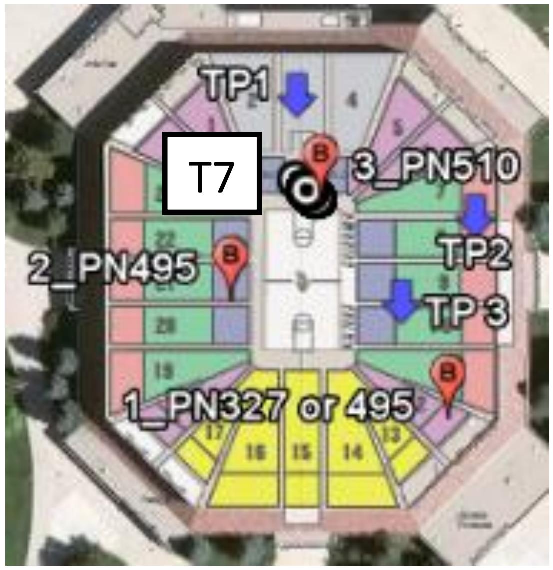

Fig. 39: All phones, Fix distribution for T7

CHAPTER 7

Comparison of User Plane to Control Plane

7.1 Introduction

The tests so far have examined the impact of adding pilot beacons to various deployment scenarios. The tests presented results for positioning accuracy in general without making a distinction between positioning for LBS and positioning for E-911. There is a lot of interest in improving the accuracy of positioning for E-911 [1]. Unlike LBS, E-911 requires positioning to be performed while simultaneously holding voice calls to the PSAP.

All the previous tests were performed on the user plane under the assumption that E-911, which uses the control plane, would perform similarly. The underlying positioning algorithms and the pilot/GPS measurement processes are identical. The difference between the user plane and the control plane arises due to the fact that the control plane uses SS7 signaling and is slower as compared to the IP based user plane. Even with a big difference in transfer speeds, the packets transferred are in the order of a few bytes [20]. A majority of the time required to compute a fix is in the 16 second search window that the phone has, to perform measurements, which are identical for the user plane and the control plane. It is also orders of magnitude greater than the PDE-MS communication delay that arises due to a slower control plane. To confirm this assumption, the positioning performance of pilot beacons in the user plane and the control plane were compared.

A subsection of the outdoor tests discussed were repeated using the control plane to check if performance (accuracy) is hampered. Starting with no beacons, tests were performed by turning on beacons successively as described below.

7.2 Set-Up and Configuration

The tests were performed in the Cockrell (COC) residence hall, which was also used for indoor testing. Two pilot beacons, one at Folsom (PN321) and the other at San Marcos (PN327), were used for these tests. Only Sector 2 of Whizzer (PN273) was used for these tests. Refer to Fig. 40 for the relative locations of ground truth, beacons and the serving base station.

Two phones, x1396 and x4597, were placed at the same ground truth position. Phone x4597 performed fixes using the user plane and phone x1396 performed fixes using the control plane. The phone running the tests on the user plane and the phone running the tests on the control plane were configured using the settings listed in Table 2 and Table 3, respectively.

GPS is always ON for the control plane tests. This is different than the majority of our user plane testing. A simple solution exists to enable an equivalent comparison between user plane and control plane position fixes. To perform a GPS type fix, the network provides assistance information about an estimate of the satellites whose signals may be received at the phone's location. For this, the phone does a non-GPS fix initially to get its approximate location and conveys it to the network, which in turn provides assistance data. Analyzing the initial fix provides a non-GPS fix, while the final fix is a GPS fix. Utilizing the control plane initial fixes enables a comparison with the user plane non-GPS fixes. For completeness, each set of fixes (each test set) was repeated with and without GPS for the user plane phone.

Fig. 40: Pilot beacons (B), Verizon BTS (V) and test locations

7.3 Tests Performed

For each test set in Table 17, the configuration of the pilot beacons and sectors that were transmitting are shown. Any non-empty MAR value for a beacon indicates that the beacon was on and used in the test with the indicated MAR value set in the BSA. All MAR values are given in units of meters. A GPS QoS value of 0 indicates GPS was OFF for the test while a value of 16 indicates that GPS was ON.

Each test was conducted by initiating approximately 100 position fix requests from phone x4597 (user plane) while 50 fixes were initiated from phone x1396 using the Rover application on the phones. The number of the fixes was fewer on the control plane since each fix takes over 75 seconds to perform. Each configuration (test set) produced a distribution of fix (position) solutions after post processing.

Table 17: Control Plane versus User Plane Tests

Test Set	Folsom MAR	San Marcos MAR	GPS QoS	Whizzer	PH1	PH2
923-1			0	X	User	Control
923-2			16	X	User	Control
923-3	1000		0	X	User	Control
923-4	1000		16	X	User	Control
923-5		1000	0	X	User	Control
923-6		1000	16	X	User	Control
923-7	1000	1000	0	X	User	Control
923-8	1000	1000	16	X	User	Control

7.4 Test Results

If the positioning on the control plane is similar to the user plane, it is expected that the error figures would be similar. Also, with the addition of beacons, for cases with GPS 'OFF' it is expected that the errors would go down. Fix types are expected to change from Mixed Cell Sector for no beacons, to Mixed Mode for one beacon and AFLT for two beacons.

The solutions in the user plane and the control plane are similar despite difference in data rates between the two, as observed in Table 18. This validates the initial assumption that performing tests on the user plane using the Rover software was indicative of performance obtained when repeatedly dialing an emergency number.

All the even numbered test cases had GPS ON and had similar accuracies irrespective of the beacon configuration. In test case 7, the average error on the control plane was nearly double that of the user plane since they were distorted due to very few fixes being performed.

Table 18: Control Plane vs. user Plane Results: Average Error (Meters)

Test Set	**User Plane**	**Control Plane**
923-1	153.7008794	154.5473215
923-2	15.21159529	13.01561486
923-3	85.75608262	79.82684206
923-4	11.20549847	12.41959431
923-5	87.91520917	93.16524592
923-6	30.91343132	15.00305827
923-7	45.97477217	83.13175339
923-8	37.50669608	15.77118141

CHAPTER 8

Conclusion

The testing effort described in this document demonstrates an alternative to the various other in-building technologies proposed. Pilot beacons offer a standards complaint solution to the poor indoor positioning performance. While the other in-building technologies, like Wi-Fi RF fingerprinting, deliver superior performance they still do not offer a credible alternative to AGPS + AFLT due to the fact that not all phones can leverage the technology.

Although the aim of this effort was not to determine the number of beacons necessary to cover the area of interest (CU campus) to guarantee a particular indoor performance, the results from Chapter [3] show that when an indoor location is able to measure pilots in addition to the serving sector, the positioning performance improves. In areas where pilots from neighboring sectors are insufficient, pilot beacons can be used to supplement the cellular network. It is observed that the actual gains from adding beacons to the network is dependent on the number of ranging sources (sectors) already available to the handset. Rural areas with large cell sizes are likely to benefit the most with the addition of pilot beacons. With just three ranging sources an improvement of nearly 40 meters was observed. Gains were much lower when successive beacons were added. Beacons that acted as the fourth, fifth and sixth reference each contributed to about 8 meters of additional improvement in accuracy. The uncertainty in the PDE's estimate of the MS position also decreased with the addition of beacons. This improvement was well behaved with the HEPE values decreasing monotonically with the addition of each beacon.

It was observed that the positioning errors varied with each test location and also with the choice of beacon added to the network, as shown in Appendix A. An observation that is common to all types of ranging measurement based solutions, including AFLT and GPS, is that the accuracy in positioning is a function of both the degrees of freedom (number of measurements available to work from) and the transmitter – receiver geometry. The effect of geometry is illustrated in Fig. 41 which shows the dependence of the uncertainty in output based on the base stations/beacons used for ranging. Take for example the observation that adding the San Marcos beacon to a configuration almost always resulted in gains in performance, while the ECOT or the Folsom beacon provided little gains or sometimes worsened the position errors. However, with just a sample of three test locations it would not be possible to categorize the Folsom and ECOT beacons as detrimental to positioning. There may be other truth positions where Folsom and ECOT may improve positioning errors.

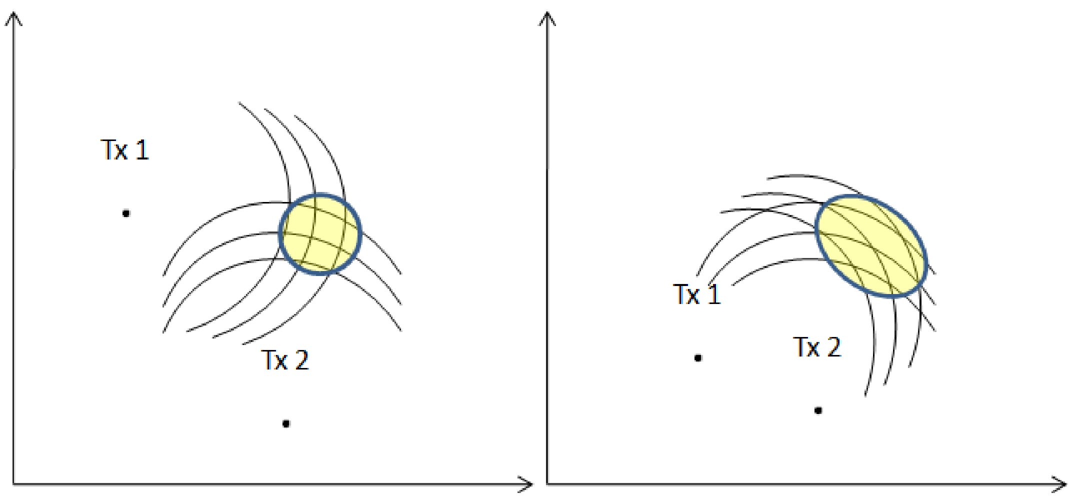

Fig. 41: Figure illustrating the impact of geometry on ranging

In geomatics-engineering applications like GPS, a distinction is drawn between the measurement accuracy and the resulting position accuracy as a result of those measurements. Dilution of precision (DOP) is the ratio of the positioning accuracy to the measurement accuracy [17]. That is the reason why GPS performs better when there are more satellites in view of the receiver. In the same way, to guarantee a particular positioning AFLT performance it may not be sufficient to have just three ranging sources. Addition of redundancy improves the chances of obtaining a high accuracy result. This is supported by the fact that the overall error on average was lowest when four beacons were used in addition to two existing sectors.

In Chapter 4, the effect of MAR on positioning accuracy was studied. This was done by altering the MAR value of the beacons in the BSA and comparing the fix accuracy. The discussion in Chapter 4 illustrates that the MAR value of the beacon relative to the MAR value of other beacons or sectors that might be combined and used in the fix will influence the output fix position. The beacons are weighted by the inverse of their MAR value.

This effect may lead to either an improvement or loss of accuracy depending on the distance of the beacon to the ground truth. This behavior is unsuitable for positioning users over a large area spread over multiple buildings. The recommendation for deployment when a single beacon covers multiple buildings is to use multiple beacons each with a large MAR to force an AFLT based solution. The only case when a beacon deployment with a small MAR would benefit positioning is when users are concentrated in a small area and the transmit power is actually scaled down to just cover the area. This would ensure that users outside the intended area (building or structure) are not placed inside the building.

This was exactly the case in the tunnel and arena scenarios tested. The tunnel tests simulated an environment where it is not possible to hear outdoor sectors and signals from the GPS constellation are absent. Coverage is provided in these areas by either repeating an outdoor sector or by deploying a dedicated base station. One of the important characteristics of relevance is the fact that a tunnel presents a scenario where users and the pilot beacons are collinear and positioning resolution is of consequence only along one axis. In the tests simulating a dedicated sector the beacons were effective in locating users to specific segments that they covered. Tests which modeled a repeated sector serving the tunnel were troublesome but certain methods, like using the repeater flag for the beacons, were able to mitigate the problem of additional delays added by the repeater and DAS. Although performance is better when the repeater flag is set for repeated signals, it compromises the positioning of users that are above ground and outside of the tunnel so that this may not be a viable parameter setting. Yet, in some dense base station locations there may be sufficient base station sectors above ground for positioning even if one of the sectors is removed from those used for ranging. Again, such decisions need to be studied carefully on a case-by-case basis to insure that positioning will function correctly for both above ground users as well as those terminals in the tunnel. A second result from the tunnel testing was the clear indication that MAR values must be entered into the BSA accurately such that if a mobile terminal reports a beacon (or any pilot), this terminal is truly inside of the sector as defined by the MAR. If a terminal reports a pilot from a location outside of that defined by the MAR and Lat/Long of the radiator as found in the BSA, then great errors will occur.

Certain buildings with a lot of indoor users, like stadiums and conference centers, will deploy either a repeater or a dedicated base station to provide necessary coverage to support users throughout the building. Unlike a tunnel, users and beacons are not constrained to a single axis and there is a possibility of receiving weak signals from GPS. Our arena tests showed that it is possible to locate indoor users to the correct indoor venue using just one pilot beacon. Positioning improvement using pilot beacons was observed for both GPS and non-GPS fixes. Our test configuration was insufficient to position users to specific areas within the arena. Still, the application of a pilot beacon along with the correct network parameters will enable the location of users inside the venue with high accuracy.

Finally, experiments were performed to compare performance utilizing the user plane and the control plane. Despite the differences in the two modes of data transfer, it was observed that the positioning performance was similar between control plane and user plane position determination messaging. Based on these results, user plane testing is equally applicable to control plane scenarios as well.

CHAPTER 9

Future Work

In this document, the technological feasibility of using pilot beacons to enhance positioning accuracy was demonstrated. Success of this idea, however, depends also on the economic viability of deploying pilot beacons on a large scale. A cost-benefit analysis needs to be performed. This requires additional testing on a larger scale over multiple truth positions to understand the beacon density that is necessary to realize the performance improvements documented in this work. Understanding the economics of pilot beacons would help develop definitive guidelines for their deployment for various scenarios. This work would be of most interest to carriers looking to deploy pilot beacons.

Positioning of users inside large venues is a scenario that would benefit from additional testing. Future work should be focused on positioning users into specific sections of the venue. The configuration of the pilot beacon radiators, if placed in optimal locations, combined with appropriate network parameter settings, could provide a higher level of positioning accuracy within a large venue. It should be noted that beacon radiator positioning for optimum location determination within a venue may not coincide with traffic radiator locations for optimum voice and data coverage within the venue. The tradeoffs between service and positioning deployment constraints should also be studied.

Finally, there remains an open (unknown) issue as to the functionality of hopping pilot beacons for the purposes of aiding position determination. Hopping pilot beacons are relatively new but have been shown to successfully trigger the transition of idle MS traffic to a new frequency. A commercial example of this is the recent femtocell products where hopping pilot beacons are routinely used to transition the idle MS to the preferred femtocell frequency. It is not clear that hopping pilot beacons can be used to reliably assist gpsOne positioning.

The concern is that when a MS performs a pilot scan, and the pilot beacon is in an OFF state (transmitting on a different frequency), then the pilot beacon will not get measured. An exploration of the timing requirements for the pilot search relative to the pilot beacon hop frequency is necessary in order to understand if this is a real issue.

CHAPTER 10

Appendix

Table 19 summarizes the performance of the different beacon configurations. As expected, some beacons perform much better than others due to their relative location to the truth position. Table 20 presents these results sorted in decreasing order of error.

Table 19: Average Error and Standard Deviation for each beacon configuration tested in Indoor Tests, Set 1 and 2

Beacon Configuration		**Whizzer**		**Whizzer + Bison**	
		Avg. Error	Std. Deviation	Avg. Error	Std. Deviation
No Beacon		210.56	34.29	161.43	37.89
1 Beacon	ECOT	170.93	26.31	127.9	44.95
	Folsom	160.78	34.94	163.55	29.58
	San Marcos	77.23	38.95	58.49	23.66
	SLHS	95.59	39.82	90.11	44.92
2 Beacons	ECOT+Folsom	146.19	25.68	163.96	42.93
	ECOT+San Marcos	56.4	16.97	98.3	51.99
	ECOT+SLHS	109.6	34.43	92.58	58.42
	Folsom+San Marcos	66.48	34.6	106.8	58.86
	Folsom+SLHS	94.33	24.4	63.58	33.19
	San Marcos+SLHS	80.37	52.66	128.33	62.43
3 Beacons	ECOT+Folsom+San Marcos	66.33	21.38	94.9	41.31

	ECOT+Folsom+SLHS	NA	NA	76.34	40.66
	ECOT+San Marcos+SLHS	128.44	52.07	156.87	61.54
	Folsom+San Marcos+SLHS	76.54	30.05	84.47	56.95
4 Beacons		NA	NA	77.39	35.69

Table 20: Beacon combinations in decreasing order of average overall error

Whizzer only		**Bison+Whizzer**	
ECOT+Folsom+SLHS	NA	ECOT+Folsom	163.96
4 Beacons	NA	Folsom	163.55
No Beacon	210.56	No Beacon	161.43
ECOT	170.93	ECOT+San Marcos+SLHS	156.87
Folsom	160.78	San Marcos+SLHS	128.33
ECOT+Folsom	146.19	ECOT	127.9
ECOT+San Marcos+SLHS	128.44	Folsom+San Marcos	106.8
ECOT+SLHS	109.6	ECOT+San Marcos	98.3
SLHS	95.59	ECOT+Folsom+San Marcos	94.9
Folsom+SLHS	94.33	ECOT+SLHS	92.58
San Marcos+SLHS	80.37	SLHS	90.11
San Marcos	77.23	Folsom+San Marcos+SLHS	84.47
Folsom+San Marcos+SLHS	76.54	4 Beacons	77.39
Folsom+San Marcos	66.48	ECOT+Folsom+SLHS	76.34
ECOT+Folsom+San Marcos	66.33	Folsom+SLHS	63.58
ECOT+San Marcos	56.4	San Marcos	58.49

Bibliography

1. FCC Report and Order, "Wireless E-911 Location Accuracy Requirements," FCC-07-166, Nov. 11, 2007.

2. 3GPP2 C.S0022-B Ver. 1.0, "Position Determination Service for cdma2000 Spread Spectrum Systems," Apr. 17, 2009. Available: http://www.3gpp2.org/Public_html/specs/C.S0022-0_v3.0_121203.pdf

3. Evennou, F.; Marx, F.;, "Advanced Integration of WiFi and Inertial Navigation Systems for Indoor Mobile Positioning," EURASIP Journal on Applied Signal Processing, Hindawi Publishing Corporation, 2006, article id. 80706, pp. 1-11, 2006
doi: 10.1155/ASP/2006/86706

4. Goud, P.; Sesay, A.; Fattouche, M.;, "A spread spectrum radiolocation technique and its application to cellular radio," Communications, Computers and Signal Processing, 1991., IEEE Pacific Rim Conference on , pp.661-664 vol.2, 9-10 May 1991.
doi: 10.1109/PACRIM.1991.160826

5. Caffery, J.J.; Stuber, G.L.;, "Overview of radiolocation in CDMA cellular systems," Communications Magazine, IEEE , vol.36, no.4, pp.38-45, Apr 1998.
doi: 10.1109/35.667411

6. Abrardo, A.; Benelli, G.; Maraffon, C.; Toccafondi, A.;, "Performance of TDoA-based radiolocation techniques in CDMA urban environments," Communications, 2002. ICC 2002. IEEE International Conference on , vol.1, pp.431-435, 2002.
doi: 10.1109/ICC.2002.996890

7. Mensing, C.; Plass, S.;, "Positioning Algorithms for Cellular Networks Using TDOA," Acoustics, Speech and Signal Processing, 2006. ICASSP 2006 Proceedings. 2006 IEEE International Conference on , vol.4, pp. 4-5, 14-19 May 2006.
doi: 10.1109/ICASSP.2006.1661018

8. Bull, J.F.;, "Wireless Geolocation," Vehicular Technology Magazine, IEEE , vol.4, no.4, pp.45-53, December 2009.
doi: 10.1109/MVT.2009.934669

9. Retscher, G.;, "Location Determination in Indoor Environments for Pedestrian Navigation," Position, Location, And Navigation Symposium, 2006 IEEE/ION , pp. 547- 555, April 25-27, 2006.
doi: 10.1109/PLANS.2006.1650643

10. Kee, C.; Yun, D.; Jun, H., Parkinson, B.; Pullen, S.; Lagenstein, T.;, "Centimeter-Accuracy Indoor Navigation Using GPS-Like Pseudolites," GPS World, Nov. 2001. Available: http://www.gpsworld.com/wireless/indoor-positioning/centimeter-accuracy-indoor-navigation-using-gps-like-pseudolites-716

11. Ocana, M.; Bergasa, L.M.; Sotelo, M.A.; Nuevo, J.; Flores, R.;, "Indoor Robot Localization System Using WiFi Signal Measure and Minimizing Calibration Effort," Industrial Electronics, 2005. ISIE 2005. Proceedings of the IEEE International Symposium on , vol.4, pp. 1545- 1550, June 20-23, 2005.
doi: 10.1109/ISIE.2005.1529162

12. Wang, S.S.; Green, M.; Malkawa, M.;, "E-911 location standards and location commercial services," Emerging Technologies Symposium: Broadband, Wireless Internet Access, 2000 IEEE, pp.5 , 2000.
doi: 10.1109/ETS.2000.916514

13. Reed, J.H.; Krizman, K.J.; Woerner, B.D.; Rappaport, T.S.;, "An overview of the challenges and progress in meeting the E-911 requirement for location service," Communications Magazine, IEEE , vol.36, no.4, pp.30-37, Apr 1998.
doi: 10.1109/35.667410

14. Biacs, Z.; Marshall, G.; Moeglein, M.; Riley, W.;, "The Qualcomm/SnapTrack Wireless-Assisted GPS Hybrid Positioning System and Results from Initial Commercial Deployments," CDMA Americas Congress 2003 Workshop II: Enhancing 3G Services Offerings with Precision Location-Based Services, Dec. 8, 2003.

15. 3GPP2 C.S0002-E V1.0, "Physical Layer Standard for cdma2000 Spread Spectrum Systems", Sep. 2009.

16. 3GPP2 C.S0010, "Recommended Minimum Performance Standards for Base Stations Supporting Dual-Mode Spread Spectrum Mobile Stations", Sep. 1999.

17. Rizos, C.;, "Principles and Practice of GPS Surveying" [Online Document], Chapter 1.4.9, September 1999. Available: http://www.gmat.unsw.edu.au/snap/gps/gps_survey/principles_gps.htm

18. Lehrer, C.; Constantiou, I.; Hess, T.;, "Exploring Use Patterns and Perceived Value of Location-Based Services," *Mobile Business and 2010 Ninth Global Mobility Roundtable (ICMB-GMR), 2010 Ninth International Conference on* , pp.107-115, 13-15 June 2010.
doi: 10.1109/ICMB-GMR.2010.64

19. Küpper, A.;, "Location-Based Services: Fundamentals and Operation," (1st Edition), Wiley, Oct 2005.

20. Moeglein, M.; Krasner, N.;, "An Introduction to SnapTrack™ Server – Aided GPS Technology," ION GPS-98, pp. 333-342, Sept. 15-18, 1998.

21. Gum, A.; Burroughs, K.;, "Wireless Choices for LBS: Control Plane and User Plane Architectures," GPS World [Online], pp. 32-41, Mar. 2, 2006. Available: http://www.gpsworld.com/lbs/infrastructure/wireless-choices-lbs-1660

22. TIA, ANSI/J-STD-036-B, “Enhanced Wireless 9-1-1 Phase II”, Nov. 2006.

23. Qualcomm, “Tracefilter2 manual,” 80-L0036-2, Rev. A, Jul. 2008.