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Project Summary

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1 Introduction

In 1997, there were over 1.8 million offenders in prisons and jails—twice as many as there were in 1987. Over four million offenders are out on probation and parole. The cost to the correctional system in controlling and supervising criminal offenders is in the tens of billions dollars. This cost is rising with no end in sight. To reduce the cost of corrections and improve supervision of offenders, first-generation home arrest electronic monitoring systems were introduced 1987. At that time 95 home arrest units were in use. In 1996 the correctional system deploys over 70,000 units.

While we have seen a rapid growth in the number of home arrest units, they are available for only 1.2% of the offender population in the correctional system. The reason for this is that the scope of first-generation systems is limited as these systems can only determine whether the offender is at or not at home. Because monitored offenders are not under permanent curfew and monitoring—so they can leave their home for work and support themselves—a window of opportunity is opened to escape supervision.

To correct the shortcomings of the first-generation systems, second-generation wide area continuous electronic offender monitoring systems have been described[1]. Second-generation systems will enable the reintegration of the offender into society while shutting down the window of opportunity that provides the offender many hours to evade supervision under first-generation systems. Second-generation systems are likely to improve public safety while decreasing the cost of corrections by substantially increasing the number of offenders under electronic supervision as an alternative to incarceration.

Another benefit to second generation systems, is that they can store in a file the offender's locations and time history. Law enforcement can use this information to exclude or include a monitored offender as a suspect in a crime by comparing crime scene events

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* Points of views in this report are those of the authors and do not necessarily represent the position of Lucent Technologies or the New Mexico Department of Corrections.

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with the offender's location history file entries.

In 1994, the National Institute of Justice (NIJ) took a pioneering step when it provided the Westinghouse corporation with a grant to explore second-generation electronic offender monitoring systems. In 1996, Sandia National Laboratories submitted, at the request of the NIJ, a five year plan to develop such prototype systems in six locations across the U.S.A[2]. Around the same time, AT&T presented an informal proposal to the NIJ to form a *consortium* that would build these prototype systems.

The necessary technology for developing and integrating second-generation systems is significantly more challenging than their first-generation predecessor's technologies. Table I describes some of the key challenges.

Table I: Second-Generation Systems Challenges

Challenges	**First-generation**	**Second-generation**
Time coverage	Intermittent	Continuous
Location coverage	Single location	Wide geographical area, diverse terrain and construction patterns

Second-generation systems will enable corrections agencies to continuously monitor and supervise offenders over a wide geographic area. As wireless technology progresses, the area of coverage of second-generation systems, could expand from isolated local jurisdictions to the entire country. In addition to tracking offenders, it could also track simultaneously:

- Corrections officers -- to increase their personal safety while they are on the job.
- Law enforcement officers -- so that they could be immediately dispatched to deal with a serious offender monitoring violation.
- Victims of the offenders -- so that they could be alerted and protected.

In recent years, the criminal justice system has begun to focus on the issue of stalking[3]. Second-generation systems could provide a new powerful tool to deal with this problem. The system could detect and alert the victim and law enforcement of a stalking event in progress[4]. Another important challenge for the system is the ability to determine the position of an individual with estimated accuracy of 50-100 meters both indoors and outdoors. Several technologies exist today for location determination (geolocation). These methods are mainly based on the propagation time of radio frequency (RF) signals. However, some technologies are based on other characteristics of RF signals. Geolocation technologies can be terrestrial or space based.

This report focuses on the time of arrival (TOA) methods as they are widely used in many geolocation techniques[5]. The position of the tags in the TOA method is determined by a set of non-linear equations that are closely related to the three-dimensional Global Positioning System (GPS) equation. These equations are usually solved by iterative techniques[6]. In 1985, Bankoft[7] proposed a closed solution to the GPS equations. Hoshen[8, 9] developed a closed solution for these two and three dimensional problems by demonstrating that the GPS and TOA problems are equivalent to the ancient Problem of Apollonius, a problem that is attributed to Apollonius of Perga, a Greek mathematician who lived in Alexandria Egypt in the third century BC. His problem was to draw an unknown circle touching three given circles. The existence of a geometric construction for the Problem of Apollonius implies that closed solution to the problem can be expressed through an equation that is not higher than second order[10].

In the section 2, we shall provide an overview of the geolocation method. Section 3 will describe existing GPS second generation offender monitoring systems. The Federal Communications Commission directive to provide enhanced 911 (E911) to cellular phone users, which has been a driving force in the development of geolocation technologies, is described in section 4. The report will present the basic architecture of second generation systems in section 5. Section 6 discusses the importance of simulation models in system development. Section 7 discusses the theoretical basis for the TOA equations of location and their relationship to the multipath problem. Expansions of some of the ideas and information provided in sections 2-7 are given in the following appendices:

Appendix 1. Second generation system requirements: databases and computer screens.

Appendix 2. System requirements: correctional agency users' perspective.

Appendix 3. Simulator manual for developing simulation scenarios.

Appendix 4. Principal investigator's impressions during visits at technology providers' facilities.

Appendix 5. The relationships between the solutions of the Problem of Apollonius and reflected signals (multipath problem).

Appendix 6. Testing of Pro-Tech monitoring GPS (second-generation) offender monitoring unit.

Appendix 7. Various slides on location services used in presentation at Instant Messaging 2000 (IM2000) in June 2000 in Boston, Location Decisions (LD2000) in June 2000 in Chicago and Voice on the Net 2000 (VON2000) in July 2000 in Stockholm.

Appendix 8. "Electronic offender tracking" slide presentation at the 129th Congress of Correction, The American Corrections Association, Denver, August 1999.

Appendix 9. "Correction Technologies in New Mexico", NLECTC, Denver, June 2000.

2 Overview Geolocation technologies

Methods that depend on RF (radio frequency) signal strength and signal timing measurements provide the basis for geolocation technologies. The following are brief outlines of the major methods used by geolocation vendors. More comprehensive discussion on angle of arrival (AOA) and time of arrival (TOA) methods are given in a special edition of IEEE Communication Magazine[11]. Appendix 4 describes first hand observation by the principal investigator of more recent technologies.

2.1 Angle of Arrival

The angle of arrival (AOA) geolocation technology is based on measuring the direction of a signal received from an RF transmitter. The direction of the incoming signal can be determined by pointing a directional antenna in the direction of maximum signal strength. Alternatively, the signal direction can be determined from the time difference of arrival of the incoming signals to different elements of an antenna.

While a single directional antenna provides only the direction of a transmitting mobile locator device, the use of two geographically separated directional antennas enables the calculation of the position of a transmitting device in a plane. In this method the position of the transmitter is determined from the known position of the receivers' antennas and the angle of arrival of the signals with respect to the antennas.

2.2 Time difference of arrival

The time difference of arrival (TDOA) of signals received at geographically separated antennas can be used to determine position. Given the value for the speed of light, we can calculate the distance between the transmitting mobile locator device and receiver antenna if the transmit and receive times are known. Using time measurement to determine position requires accurate clocks. An error of one microsecond in time corresponds to 300 meters error in space.

Furthermore, all clocks that are used for the measurements have to be synchronized. Because synchronizing the mobile locator device clock is not a practical option for most applications. TDOA requires at least 3 receiving antennas to determine the position of the mobile locator device.

2.3 Global Positioning System (GPS)

The Global Positioning System (GPS), which consists of a constellation of 24 satellites, as in TDOA employs signal timing to determine position. In the GPS system, the mobile locator device is a receiver and the orbiting satellites are transmitters. The GPS satellites orbit the earth at a distance of about 20,000 kilometers.

To determine its position, a GPS receiver calculates its x, y and z coordinates as well as t, the time of arrival of the GPS signals at the receiver. This requires solving 4 equations for the 4 unknown values (x,y,z,t). These 4 equations require data acquisition from 4 observable GPS satellites. The computational accuracy can be improved if more than 4 GPS can be included in the computation. However in this instance, the number of equations exceeds the number of unknowns and an optimal rather than an exact solution is derived for the system of equations.

In recent years, GPS has revolutionized navigation. Yet, conventional GPS receivers have only a limited use in mobile personal locator devices. Because GPS signals are weak, the GPS receiver requires an unobstructed line of sight contact to the GPS satellites. This generally precludes the application of GPS receivers inside buildings. Another disadvantage of conventional GPS receivers is that it could take several minutes to achieve the first acquisition of the GPS satellites' signals. Because of the long acquisition time, GPS receivers tend to operate in a continuous mode rather than turning the GPS receiver on an off for each acquisition. Such continuous operation imposes a significant drain on the receiver's battery.

2.4 Assisted GPS

To overcome these shortcomings of conventional GPS receivers, an innovative technique known as server assisted GPS has been introduced in 1998. Assisted GPS includes a stationary GPS server that assists the mobile GPS receiver to acquire the GPS signal. The server includes a GPS receiver, whose antenna is placed in an unobstructed view of the sky, and a radio interface for communicating with the mobile GPS receivers. This stationary GPS receiver can continuously monitor signals from all the observable satellites. Whenever the server requests a position of a mobile GPS receiver it transmits GPS satellite information through its radio interface to the mobile. Within about one second, this process allows the GPS receiver to collect sufficient information for geolocation computation. After the mobile receiver completes its collection of information, it sends it back to the server. The server can then combine this information with data from the satellites' navigation message to determine the position of the mobile.

The advantage of the assisted GPS approach is that the mobile receivers are not required to continuously track the satellites' signals, thus, conserving valuable battery power. Yet, the most significant benefit of assisted GPS is that it effectively raises the receiver sensitivity to allow acquisition of GPS signals inside most buildings. In addition to reducing power consumption and improving signal tracking, assisted GPS technology offers improved accuracy over conventional GPS. Because the position of the stationary GPS receiver is accurately known, the difference between its measured position and its actual position can be used to calculate a correction to the position of the mobile receiver.

2.5 The enhanced signal strength method

Computing the position of a mobile locator device in the absence of obstructions, is a straightforward process for both signal timing and signal strength methods. When timing is used, the signal propagation time between the two points multiplied by the speed of light gives the distance between the two points. For signal strength methods, the distance between two points can be determined from the signal attenuation between the points. However, the ideal situation of unobstructed direct line contact does not exist in most siturations. In these situations, signal attenuation is usually unknown and many indirect paths between transmitter and receiver can exist. While techniques exist for reducing multipath effect, this effect cannot be eliminated. Furthermore, it is difficult to predict the errors that are produced by the multipath effect.

One signal strength technology, which is presently implemented for the wireless Personal Handy Phone Systems (PHS) in Japan, has developed an enhanced signal strength (ESS) method that overcomes impediments such as multipath, attenuation, and antenna orientation. Using a 3-dimensional information on land topography, buildings, elevated highways, railroads and other obstructions, the system simulates the RF signal propagation characteristics for each PHS transmitting antenna in the coverage area. The results of the simulation are stored in an RF database. To determine the position of the mobile locator device, the mobile device measures the signal strength of preferably 3 to 5 base stations. Using the signal strength and the base station database information, the system calculates the position of the mobile locator device.

2.6 Location fingerprinting

In contrast to the conventional geolocation approaches that depend on signal timing or strength, US Wireless of San Ramon California has developed a new technique that rely on signal signature characteristics. US Wireless found a way to take advantage of the mulitipath phenomenon for developing geolocation technology. It developed a proprietary technique known as location fingerprinting (LF) that uses signal multipath pattern and other signal characteristics to create a unique signature for a given location. To exploit signal signature characteristics in geolocation, US Wireless has introduced the RadioCamera system. The compiles a unique signature for each location point , which covers approximately 30 square meters. The signatures are then stored in the signature database.

When the RadioCamera system determines the position of a mobile transmitter it matches the mobile's signal signature to an entry in the signature database. Unlike methods, such as AOA and TDOA, where multiple point signal reception is necessary, the RadioCamera system requires only data from a single point to determine location. Moving traffic (vehicles, animals or people), changes in foliage or weather do not effect the systems capabilities.

3 Second Generation Offender Tracking Systems

In 1997 two companies, Advanced Business Sciences (ABS) of Nebraska and Pro Tech Monitoring of Florida were the first to introduce GPS based continuous monitoring systems for criminal offenders. These systems are deployed among others, in some localities in Michigan, Minnesota, Florida, Colorado, Wisconsin, Pennsylvania, South Carolina, Arizona, Ohio, Texas and Nebraska. More recently BI Inc. the leading manufacturer of first generation offender tracking system began testing their version of GPS based system.

The Pro-Tech Monitoring, ABS, and BI GPS offender monitoring systems are similar in concept. They include a personal locator component, telephone wireless interface and a location center. The personal locator component consists of two physically separate parts, a GPS unit and an ankle bracelet shown in Figure 1. The ankle bracelet, which employs a temper detection circuitry, uses a low power transmitter covering a range of about 50 meters. The GPS unit consists of a GPS receiver, a wireless telephone component and a receiver that detects the bracelet signal. The offender carries the GPS unit in his or her hand, or in the case of the ABS system, the unit can be worn on the Offender's belt. In the event the GPS unit fails to detect the bracelet signal (most likely due to physical separation that exceeds the bracelet transmitter coverage area) or the bracelet circuitry detects tampering, the GPS unit alerts the location center via its wireless interface. Furthermore, the GPS unit monitors its position via its GPS receiver whenever the GPS satellite signals are detectable, which is mostly outdoors.

The GPS unit can operate either in autonomous mode or in data packet mode. In autonomous mode, it logs the position of the offender in its internal memory. It compares this position with onboard database of exclusion and inclusion zones. When it detects a zone or other violation, it initiates a wireless call to the location center alerting it of the infraction. In the autonomous mode, once or twice a day, the GPS unit dials the location center to update it with the logged data that it collected. The reason for operation in an autonomous mode is to avoid the costly voice type wireless connection. Using the significantly less expensive packet based CDPD (Cellular Digital Packet Data) wireless telephone connection, the GPS unit operating in data packet mode can maintain a continuous real-time contact with the location center. Unfortunately, CDPD is not available in many areas.

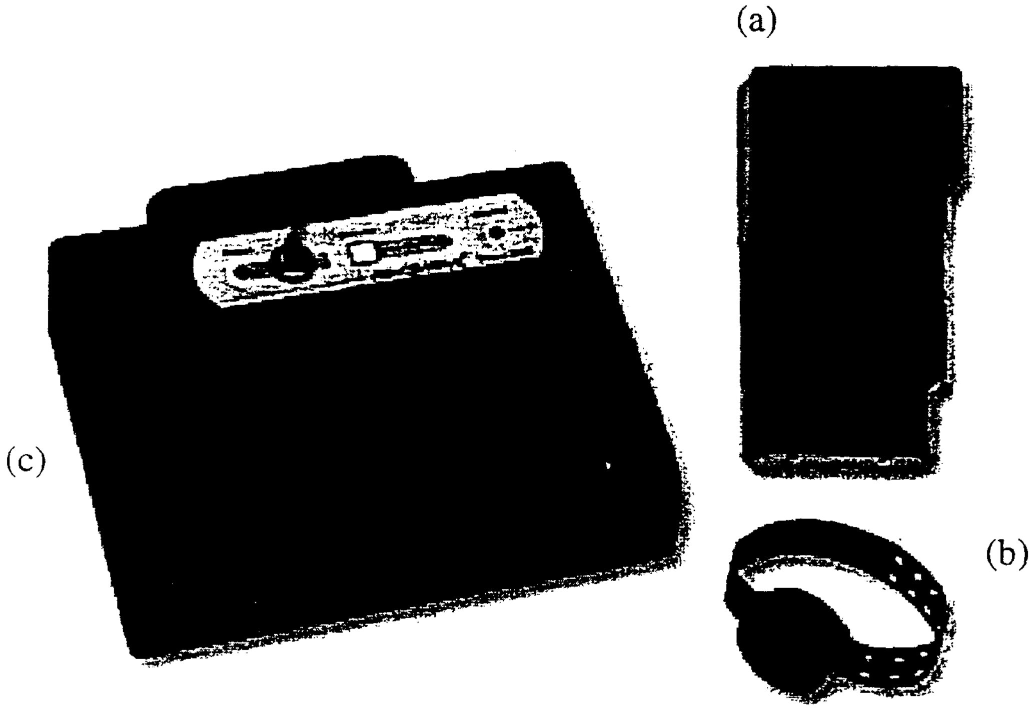

Figure 1: Locator components of ABS offender monitoring system: (a) Belt wearable GPS unit weights 0.79 kilogram with battery charge of up to 48 hours (b) Ankle bracelet (c) Docking station for GPS unit recharging (includes remote alcohol tester). (Courtesy of ABS)

The split of the locator device into two components, the bracelet and GPS unit, might be less convenient for the offender. Yet, it offers a simple recharging strategy for the GPS unit batteries, which usually requires a daily recharging to provide power to both its GPS receiver and wireless telephone interface. At night when the offender is required to be at home, the GPS unit is placed in a docking station, such as shown in Figure 1. While in the docking station, the unit's battery is recharged. During the recharging period, the GPS unit can establish contact with the location center whenever it detects violation

4 Wireless E911

The need to provide 911 service to wireless telephone users has been a major driving force for developing location technologies in the US. Today when a landline caller in the USA makes an E911 (Enhanced 911) emergency call, that call is routed to a public safety answering point (PSAP). The PSAP matches the caller's number with telephone number entries contained in an automatic location information (ALI) database. When the match is made, the ALI provides the PSAP with the street address, and a specific location in a building such as floor or office of the caller handset. The capability to rapidly provide the location of the caller enables the emergency crew to respond with an average of 5 to 7 minutes to the emergency call.

Because wireless handsets by their nature are mobile, a simple database relationship linking a telephone number with location is not possible. Thus, the response time to a wireless call takes 10 times longer than a landline call. Clearly such a delayed response is not acceptable in emergency situations.

To reduce the response time for an emergency mobile call, the US Federal Communications Commission (FCC) directed the wireless telephone service operators to provide location capabilities for E911 services. The directive specifies two phases. In phase I, the FCC required an accuracy of several kilometers by April 1998. In phase II, by October 1, 2001, the directive specifies an accuracy of 125 meters with 0.67 probability. While phase I could be accomplished with only software changes to the system, phase II requires incorporating new location technologies.

The FCC original directive required the support of the legacy handsets. The implication was that only network upgrades are acceptable because it would be very difficult or impossible to upgrade the legacy handsets in the field. Yet, a complete network solution will preclude the use of emerging technologies such as assisted GPS because they require also handset modification. To facilitate the introduction of new technologies, in September 1999, the FCC modified its original directive and allowed handset-enabled solutions. The modified directive also tightened the accuracy as shown in the following Table II.

Table II: Accuracy required by the FCC directive for wireless E911 services

% Calls	Network Solution	Handset Solution
67	100 Meters	50 Meters
95	300 meters	150 Meters

5 The System

Figure 2 present a model for a one cell second-generation system. It consists of the following components:

- Service center - maintains information and communication with participants wearing location tags. It is responsible for sending requests to tags through the interrogator transmitter. It receives responses from the tag through the receivers.
- Interrogator transmitter - transmits requests from the service center to tags.
- Locator tags - portable units worn by the tracked participants. The location of the participants is established via communication between the service center and the tags.
- Receivers and their antennas (terrestrial systems)- time synchronized receivers intended to record the time at which packets arrive at the receivers from the tags.
- Data links - wired or wireless links connecting the receivers to the service center.
- GPS Satellites (space based systems) – Transmitting satellites. GPS Satellites are included if GPS or Assisted GPS is used in the system.

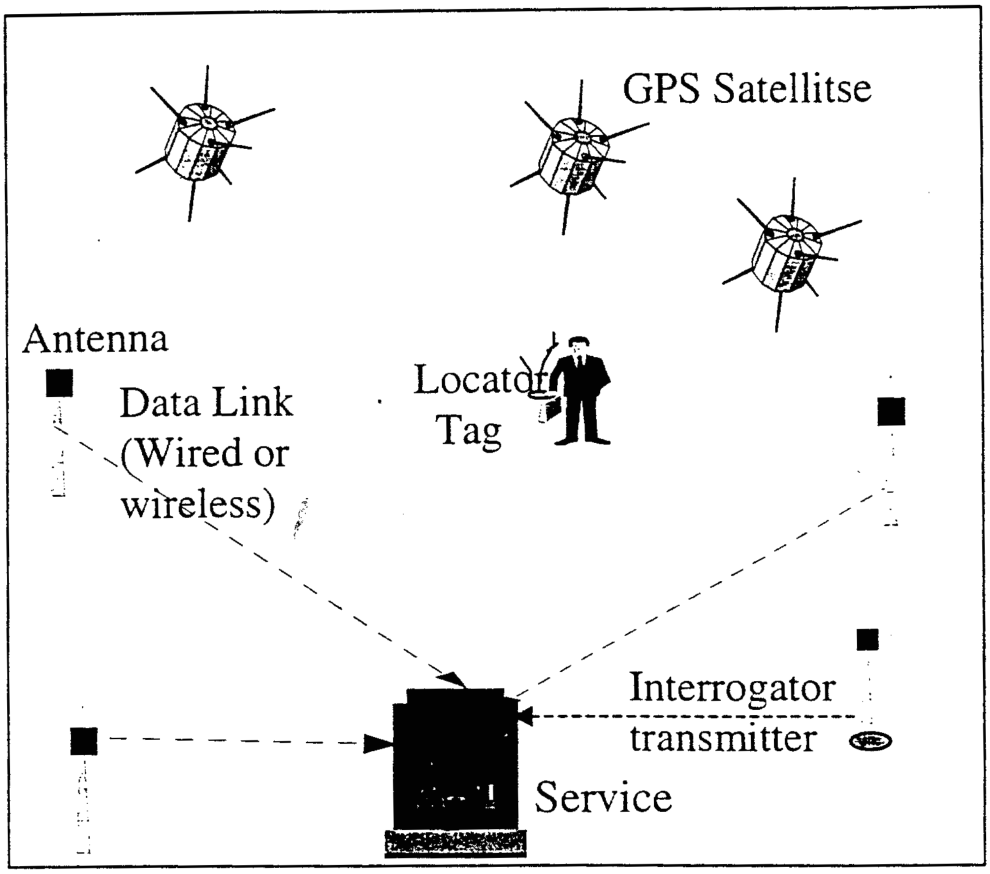

Figure 2: Prototype System Architecture

The systems considered here could be land based, such as TDOA, AOA, ESS, GPS, assisted GPS or Fingerprinting. However, the **focus** of the simulation model of this report is on the **service center** rather than the geolocation technology.

5.1 Service Center

The service center high level architecture is shown in Figure 3.

The basic components of the prototype service center consist of:

1. A computer
2. A data base management system (DBMS)
3. A computer console
4. An interrogator/receiver interface for sending requests to tags through the interrogator transmitter.

The role of the service center is to keep track of the positions of tagged participants listed in its database. The position of the participants is determined through communication between the service center and the tag. The user interfaces with the system via a collection of display windows that are invoked through pop-up menus on the service center console. The windows include both text and geographic map entities. The user access to the windows is through the keyboard and a Graphical User Interface (GUI) such as a mouse. The console also allows the user to access and update of the system's DBMS.

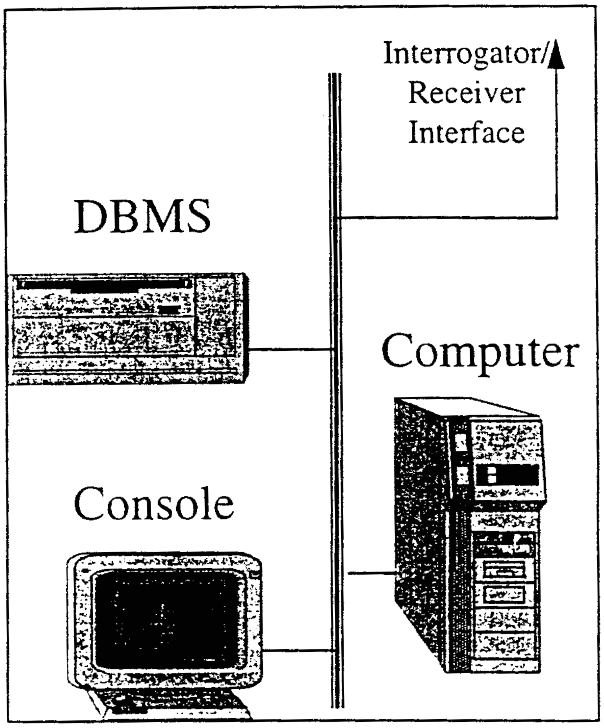

Figure 3: Service Center Architecture

5.2 Zones and Paths

A very important element of the tracking system is monitoring areas in which the offenders are permitted or restricted. These areas fall into several categories:

1. Permitted zones
2. Exclusion zones.
3. Permitted paths.

Figure 4, which shows a section of Albuquerque NM, illustrates the roles of some of these areas and an offender tracking scenario associated with these areas.

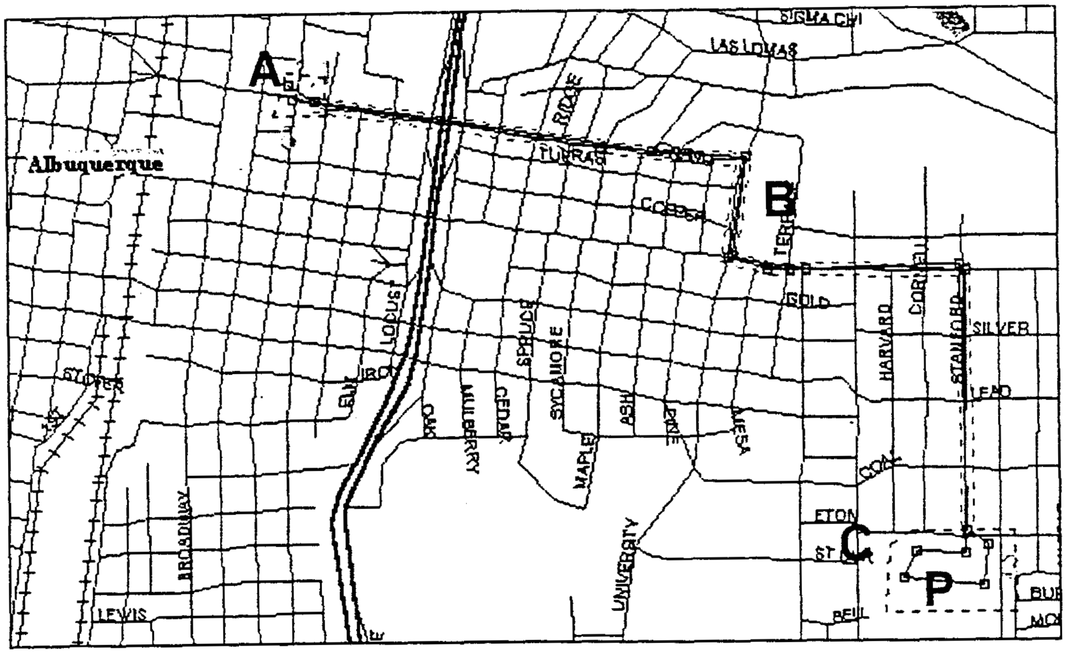

Figure 4: An Example of Permitted Zones for an Offender Tracking Scenario

Figure 4 describes the following simulation scenario: (1) the offender leaves home, **A**; (2) on the way, **B**; (3) at work, **C**; (4) returning on the way back, **B**; (5) back home, **A**. In the figure, **P**, the solid line, depicts the movement of the offender within the permitted areas.

In the simulated system, zones are described in terms of polygons. Connecting paths are described in terms of polylines (open polygons). These geometrical objects can be defined with infinite precision. Yet in reality, location determination, due largely to multipath effects, given with a finite resolution. Quoted values for this resolution are scattered around 100 meters[5]. The proposed model is designed to recognize this uncertainty and prevent false alarms that it could lead to.

6 Offender Monitoring Simulation Model

Simulation models and simulators have been valuable tools for developing and analyzing complex systems. They are being used in many areas of science and technology from nuclear plants to biomedicine. Fairchild and Clymer enumerate thirty one benefits of computer simulations and simulators[12]. They list among others cost savings, design studies, training and faster and safer startup. A simulation model for the tracking system will help:

1. Clarify architecture, requirements and design issues.
2. Plan for potential corrections' scenarios before the system is deployed.

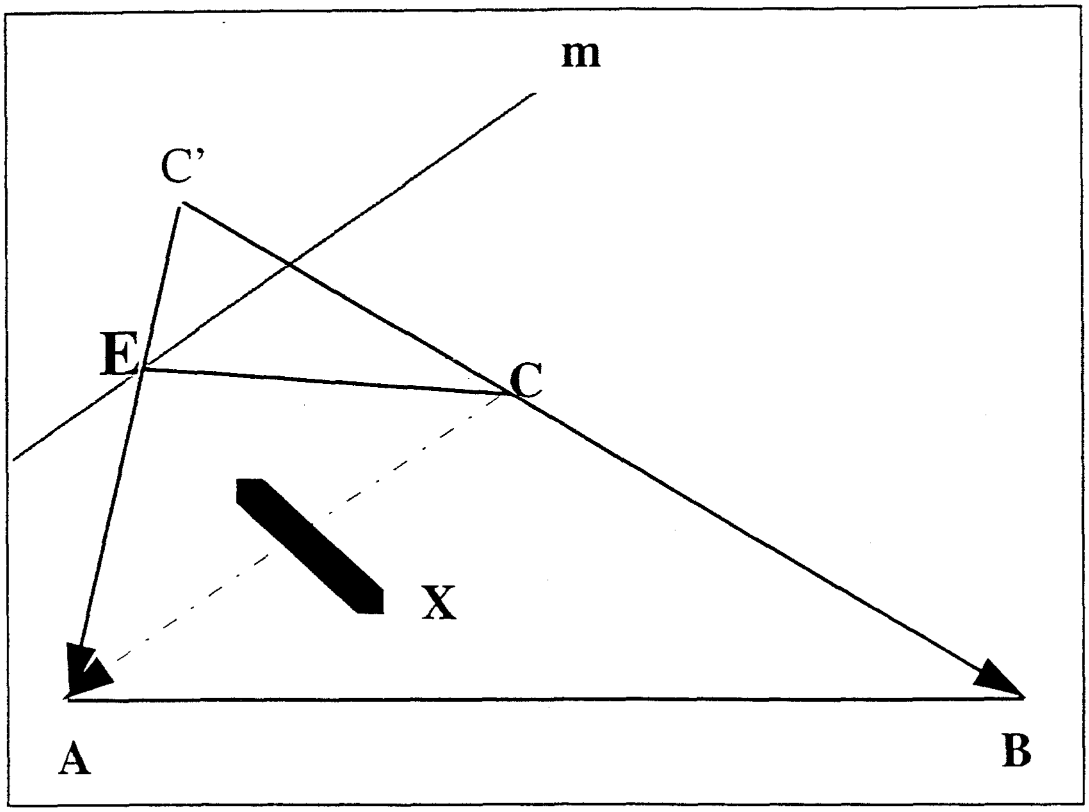

Figure 5: Reflections Scenario in AOA System

In Figure 5, mobile unit **C** transmits. Fixed stations **A** and **B** receive this signal. If there are no obstructions for transmitted signals, we can get the position of **C** from a simple geometrical construction. Yet, In Figure 5, we assume that an obstruction **X** blocks the direct line of sight AC and a mirror ***m*** reflects at **E** the signal from **C** to **A.**

We have seen that for the AOA method, we get a solution to the location problem even if this solution deviates significantly from the true solution. The questions of interest are:

(a) What are the geometrical implications of reflections on the solution of the TOA problem?

(b) Can the answer to (a) improve our ability to reduce the effects of multipath on the positioning solution?

Hoshen[10,11] in has shown that the external tangency of the Problem of Apollonius is related to the direct signal solution of the TOA problem. Appendix 5 explores the entire 16 solutions of the problem of Apollonius and their relationship to the direct and indirect signals in the TOA/GPS methods. An abbreviated analysis of these solutions is also available[13]. While the analysis of Appendix 5 establishes theoretical relationship between the internal and external tangencies and the TOA/GPS problems, this theoretical relationship does not appear to have practical implication. The reason is that reflected signals still require detailed knowledge of the geometry of the signal path environment.

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