CONTEXTUAL GEOLOCATION: A SPECIALIZED APPLICATION FOR IMPROVING INDOOR LOCATION AWARENESS IN WIRELESS LOCAL AREA NETWORKS

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ABSTRACT

The future of computing includes "adaptive" menu structures for applications that will automatically select content and navigation options – as desired – based upon the location of the user. With wireless systems, location awareness improves networking efficiency and helps alleviate the notoriously slow process of inputting information into handheld computers. For example, a security guard could have a wireless device that automatically presents him with a list of authorized occupants or equipment as he walks toward a specific room.

Along with speech recognition technology, location-based services are revolutionizing the capabilities and ease of use of mobile devices. In order for location-based services to be offered consistently to consumers, a reliable indoor wireless geolocation infrastructure must exist. This paper describes a contextual geolocation application using RF fingerprinting and an intuitive indoor geographic information system for improving indoor location awareness in wireless local area networks.

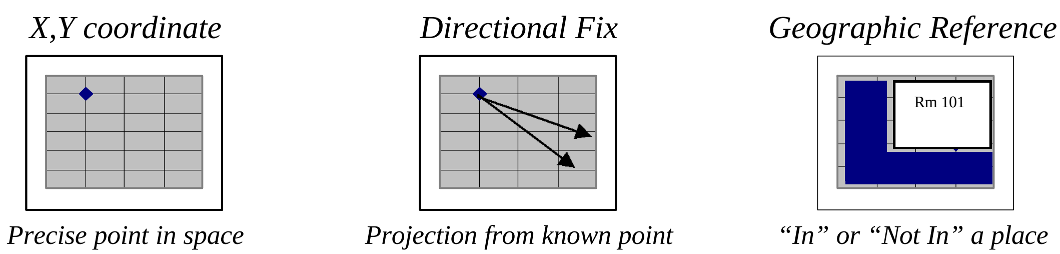
1. RESEARCH

1.1 Indoor Wireless Geolocation

1.1.1 Level of Location Detail

A wireless-enabled device can be located in a physical area – to varying degrees of accuracy – with the assistance of software that interpolates or estimates the device's position based upon measurable wireless transmissions. Different algorithms are used to translate recorded signal properties into distances and angles, where trigonometric functions can come into play. Examples of location interpolations to varying levels of detail are X-Y coordinates, directional fixes, or relative geographic references. In this paper two primary location interpolation techniques are examined: triangulation and fingerprinting.

Figure 1.1: Interpolations of location to varying levels of detail



1.1.2 Location by Triangulation

The art and science of geolocation by triangulation has been around for eons. Long before the existence of GPS units (global positioning system), sailors navigated ships by fixing their relative position according to the sun, stars, and landmarks. Triangulation is a generally used term for trigonometric comparisons of objects with known and unknown positions in order to estimate the unknown values *(See Figure 1.2)* [9].

In wireless networks, the straightest path ("direct line of sight" or DLOS) between objects is often difficult to ascertain. The strongest signal – the one the mobile device is using to bind to the network access point (AP) – may have bounced off a nearby wall, while the DLOS path – the shortest route – may have been drowned by RF interference [11,12,13]. Such "multi-path" effects complicate indoor and outdoor wireless geolocation. In some cases, researchers create special algorithms just to determine how many walls an RF signal has passed through or bounced off of in order to estimate DLOS distances for triangulation [6].

Figure 1.2: Location interpolated by triangulation

Two Known Points and One Unknown Point | **Known Values Help Deduce Unknown Values**

*Known (**1 & 2**)*
*Unknown (**S**)*

***Angles S12, S21** & **Length 12** help estimate the distance to Point S*

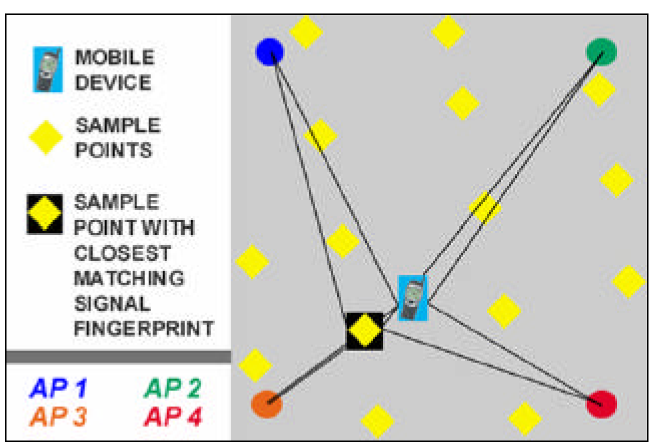
Direct Line Of Site (DLOS) distance calculations contain multiple levels of computation

A triangulation-based geolocation system may use a database to store values about distortions in RF signal propagation throughout a building. The position of walls and other interference can be modeled in the database in order for the geolocation system to predict propagation effects. This assists geolocation algorithms by filtering out or correcting known anomalies in signals, so DLOS triangulation can be more accurately performed. In essence, determining location relative to known points is a fairly simple trigonometric function; compensating for errors and anomalies, however, often requires many additional computations [12].

1.1.3 Location Fingerprinting

An alternative to DLOS and triangulation-based geolocation approaches is *location fingerprinting*. Fingerprinting is matching of one set of measurements with another "reference" set contained in a database. In other words, a mobile device takes a "snapshot" of signals from visible APs for comparison with reference points stored in the database. A common signal modeling approach is to record samples of wireless signals from points in a large grid drawn to encompass either the entire floor or occupied areas of a building [2,6,7,12,14]. The smaller the grid cell size, the more samples are stored in the database.

Figure 1.3: Location Fingerprinting Using a Casual Grid of Spatial Reference Points



In spite of the additional load that databases present to a computing system, fingerprinting – a database-centric approach – has good applicability for indoor positioning systems, given the complexity of triangulation considering indoor wireless propagation patterns over time [11]. For any database-oriented approach, simplicity of the reference schema is a perpetual goal.

1.1.4 Indoor Wireless Environments

Currently, wireless signals in the 2.4GHz band are typical for local area, wireless voice and data appliances. At this frequency range, interference from nearby electrical equipment – as well as structural features such as walls – regularly impede wireless transmissions [6,7,12,13]. In a distortion-free environment, signals from two or three access points provide enough information to determine location to a useful level of detail. Indoors, however, certain characteristics complicate wireless signal behavior:

Figure 1.4: Challenges to Indoor Geolocation

- Wireless signals are reflected and refracted, creating multi-path interference
- Precise building reference floor plans increase system complexity
- Budgetary constraints limit the total number of APs in a network
- Many geolocation techniques are designed only for outdoor applications
- Building construction, number of occupants, RF interference, and traffic demands degrade radio signals in a difficult-to-predict manner

These generalizations about indoor wireless networks – primarily 802.11b (or “Wi-Fi”) and Bluetooth – do not necessarily apply to wireless phone systems, such as GSM and CDMA. The long range (up to 30 miles) of wireless phone transmissions, however, makes them mathematically unsuitable for precision indoor geolocation, where 50 to 100 meters in 3D space is a significant margin of error [16]. 802.11 networks – with a range of up to several hundred feet – are appropriate for building and campus wireless geolocation systems. Bluetooth networks provide an underpinning for sharing information among devices located within 3 meters of each other, and could allow multiple devices to share one 802.11b network connection and determine “pico” positioning around a device with known location attributes. Basically, the concepts proposed in this paper are network-agnostic, and several methodologies of indoor wireless geolocation are discussed.

1.2 Applications for Location-Aware Devices and Systems

1.2.1 Advantages and Expectations

A number of practical benefits result from the ability to determine the location of a wireless-enabled, mobile device as it navigates throughout a wireless network. Service and infrastructure uses, such as wide-area security, inventory control, emergency response, event management, and wireless commerce are natural applications. Plus, user interface improvements – adaptive menus and navigation that save time and convenience – help overcome slow information input. Network performance enhancements, derived from preemptive caching of content based upon a better spatial understanding of user activity, increases speed and encourages optimum placement of APs. And, location-aware mapping applications help people know where they are and need to go. Because of this vast potential, there is a current and compelling need for broadly adoptable indoor geolocation methodologies that can integrate with private and commercial information systems and software products.

Precise indoor wireless geolocation tends to have high costs, in terms of additional processing power, required equipment, or increased system latency. For geolocation systems that do not employ IR (infra-red) or RF (radio frequency) beacons or other specialized equipment, accuracy to within one meter should be considered excellent [2,11,12]. The E-911 cell phone-based emergency location system – as specified by the FCC – anticipates a maximum accuracy of 50 to 100 meters or more in good outdoor coverage areas [16]. This E-911-mandated accuracy might not consistently locate individuals inside a particular room in an apartment building, but it will surely help find people lost in the woods. Geolocation accuracy can be understood, therefore, as a relative parameter. For example, if an EMS team is responding to an emergency, the immediate question is whether or not someone is inside the burning building. If yes, then exact and real-time geolocation of the wireless 911 caller(s) becomes especially critical, given the mission of rescuing people from inside the burning structure. The need for timely and contextually precise positioning systems is not only a goal of public safety and telecommunications infrastructure providers; geolocation software yields a host of information management benefits in many industries.

Ultimately, the capability and applicability of a geolocation system is limited by the technologies and approaches it employs, the extra equipment it requires, and the responsibilities it imposes on users. From an application perspective, the level of detail required varies in different scenarios, and precision and performance tend to trade off. It is the norm to sacrifice detail in order to gain speed [12]. In the world of mobile and wireless devices, processing efficiencies are especially important, as processor speed, memory, battery power, and bandwidth are relatively scarce commodities. Plus, handheld device displays tend to be small – even monochromatic – presenting challenges to meaningfully representing information.

One advantage of location-aware devices is their ability to “geocode” application information, which is the heart of an auto-adaptive mobile application menu system. Auto-adaptive menus mean users click fewer menu items and input less data without sacrificing interactivity or productivity. Even experienced typists work miniaturized, handheld computer interfaces more slowly than full-size QWERTY keyboards. Faster input technologies, such as speech recognition and virtual keyboards, will go hand-in-hand with advances in location-aware systems. A major obstacle to the proliferation of wireless mobile devices will be overcome when the problem of slow input of information is solved [3].

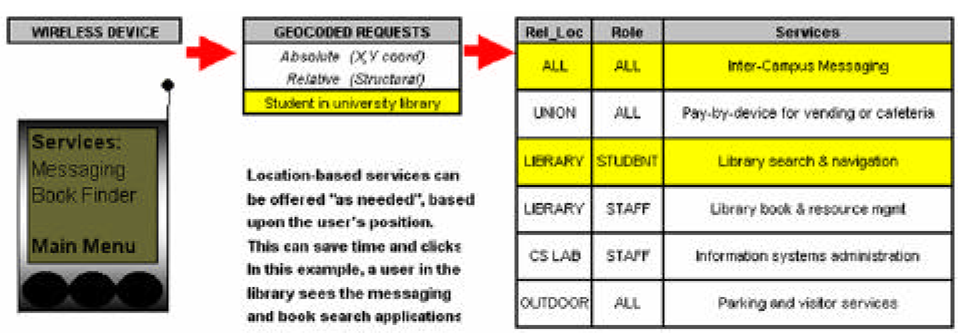
Among other characteristics, wireless signals are never guaranteed to be present in the same quantities at all times, especially as device location changes. In fact, large campuses and even cities will probably have persistent pockets of poor terrestrial-based wireless coverage (geographic terrain, structures, interference, planning decisions) [13]. But, even when a signal has insufficient Quality of Service (QoS) to transmit data with acceptably low bit error rates, it still tends to be measurable. An indoor wireless geolocation system can leverage the presence all visible APs and not just the closest one.

Perhaps most importantly, a wireless device will undergo periods of separation from a wireless network. Occasionally, signals are lost and batteries weaken. Behavior under these circumstances – what functionality is still available – is the critical litmus test of a mobile application. Location awareness should not be completely lost during periods of "disconnected" operation, especially if one aim is to put technologies on the market that people will like, use, and adopt. In terms of location-based services as an innovation, consistency of user experience will substantially affect the timeline for mass public acceptance [3,4,13]. A mobile geolocation application, in which the device contains the tools to locate itself, must therefore be designed with these limitations in mind.

1.2.2 Geolocation and Geographic Information Systems

For the past twenty years and more, geographers have been applying computer science and engineering techniques to understanding the spatial relationships between humanity and the planet. William Drummond, a noted geographer, described the great strides that spatial analysis technologies have brought to the area of urban planning. He also observed that most geographic awareness and innovation have escaped regular, everyday users because of the difficulty with "generating accurate, timely, and inexpensive locational information for human activities" [4]. Today, the potential of location-aware applications has yet to be fully realized. But, the contribution of geographic information systems (GIS) to the problem of geolocation is apparent when considering what will result once precision, on-the-fly geolocation becomes possible: a location-based service can be defined as an *attribute* of a user *location*.

Figure 1.5: Menu of Location-Based Services in the Context of GIS



Understanding wireless services as an attribute of location means that, in sparse areas, there may not be any location-pertinent services available even if there is wireless coverage. In these cases, the geocoded application database would have no services listed for a specific location (and security role). For the user, this means that no “proximity-controlled” menu items would appear on his location-aware device. In densely populated cities or campuses, though, the available wireless service attributes for a given location could be robust. Systems such as email, SMS and MMS (short messaging service and multimedia messaging service) will inevitably be available wherever the wireless-enabled device can connect to the network. Messaging and other solutions need not be sensitive to user location. Thinking of location-aware services in terms of a GIS model – where each service has locational availability, security, and other descriptive attributes – provides powerful insight into the design and deployment of location-based services and the software systems that will run them.

1.3 Technical Approaches to Indoor Wireless Geolocation

1.3.1 Discussion of Available Metrics

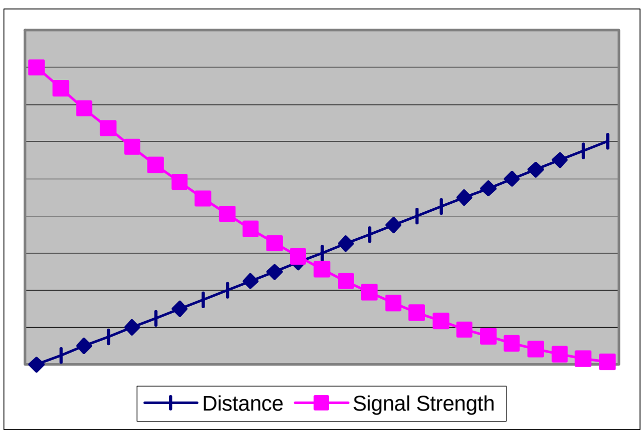
This paper focuses on geolocation for users of wireless, handheld devices rather than notebooks or laptops. Handheld devices have more frequent usage patterns, greater mobility, and more on/off activity than laptop PCs, which tend to be relatively stationary when in use [13]. In other words, solving location problems of handheld devices, which are also harder to locate, simultaneously solves the problem of locating notebook computers [2].

Accurately locating a mobile computer within a wireless network faces several technical challenges. First, RF signal parameters must be readable from the mobile transmitter by software via an API, which may not be publicly available. Through existing or additional hardware, measurements such as phase of arrival (POA), angle of arrival (AOA), time difference of arrival (TDOA), or received signal strength (RSS) can be used to determine position relative to the known position of the APs. Specially designed, “directional” antennas, as well as software-based geometric probability algorithms and “ray tracing”, can determine the AOA [6,13]. Since signals move at a fairly constant rate, time and distance are directly related. Precision clock measurements and timed transmissions between devices and APs yield TDOA and other time-based calculations that are useful for finding distances between transmitters, as well as which signal in a multi-path environment is DLOS (it will have the shortest round-trip transmission time) [10]. Each of the above approaches has specific utility for certain geolocation applications.

The main goal of indoor wireless geolocation is to orient wireless-enabled devices to the most fixed locations possible and at the most reasonable cost. Without extra equipment – such as optical, RF, infrared, or ultrasonic beacons – the only locations visible to a device are wireless access points. GPS systems alone are not practical indoors, because they depend upon signals from satellites in order to triangulate position and only perform well outdoors. Other geolocation methods exist, however. For example, if a person is using a wireless handheld computer that is transmitting via an access point with an ID# of 12345, then the user can be located as within transmission range of AP #12345. This is an aspect of the "cell-id" location method. Similarly, if a device can detect signals from two APs that are known to be relatively far apart, then the device's location can be described as somewhere between these two APs. Decreasing precision in favor of logical statements such as "between object A and B" is a powerful cell-id-base interpolation method [5,16].

The most straightforward method of determining indoor location is probably measuring the received signal strength (RSS) between devices and APs and comparing the value to the original transmit power of the signal. Since radio signals decay in a predictable pattern (not considering effects of RF interference or noise), it is assumed that distance can be determined by the "dimness" of a wireless signal. This is analogous to astronomers guessing how far a star is from Earth by estimating its actual luminescence and then measuring how much light has reached the astronomer's instruments. For wireless networks, researchers have developed formulas for signal propagation based upon empirical observations. With a minimum number of viewable APs for a given location, a geolocation system can apply trigonometry to distance-interpretations based on RSS, often aided by a database or other algorithmic representations of the network topology.

Figure 1.6: RSS Decreases as Distance between Device and AP Increases



D = distance
s = signal strength

$$D = 0.0163 * s^2 - 2.3s + 80$$

Source: This empirically derived indoor RSS model was developed at Carnegie Mellon University Institute for Complex Engineered Systems for their 802.11b network [14]. Other models include such factors as number of intersecting walls [6].

One complication is that, while astronomers can assume a DLOS to their target object, this cannot be assumed with RSS geolocation approaches. Signals bounce around, and it is documented that the strongest signal a device receives – the one that is used to bind with the wireless networking appliance – is not always the DLOS signal from the transmitter [7,11]. However, signal strength may be the easiest metric to record on an "ordinary" mobile device, since it is directly applicable to a device physically gaining access to a wireless network. For this reason, RSS is a favored – though not completely understood – wireless geolocation metric [12]. Although the DLOS path between the mobile device and the transmitter is not determinable by RSS, this technique is suitable for propagation modeling and location fingerprinting.

Because buildings and wireless networks occupy three-dimensional space, it is necessary to determine location vertically as well as on a horizontal X-Y plane. Shifts and dispersions in signals result in geolocation errors that cause perceived locations to “float” in three dimensions around actual physical locations [2,6,12]. In GPS, with satellites many miles away, this phenomenon is referred to as EPE (estimated position error), and can vary from zero to several hundred feet at any given time. Errors and fluctuations in wireless coverage are tied to topography, weather and other factors and are the expected norm [13]. In other words, wireless networks actually behave like moving targets. A useful geolocation system based solely on sensing signal strength from APs – and not relying upon additional equipment – can utilize a database in order to rationalize unpredictable and changing network characteristics over time.

A wireless geolocation system must take available metrics and apply a methodology for translating on-the-fly measurements into angles, distances, location fingerprints, or other spatially descriptive formats. In a basic sense, access points provide the signals and locations used for geolocation, but their limited number combined with propagation anomalies compel the application developer to think of effective and replicable ways to simplify geolocation system components while still allowing them to rationalize the uncertain nature of wireless signal propagation.

1.3.2 Geolocation Application Infrastructure

A location-aware theft prevention system in a warehouse is fundamentally different from a system that allows a user to save navigation clicks on his mobile device when paying for lunch in a cafeteria. This paper contrasts systems designed to control and protect objects and property from those aimed at enhancing human communication and mobile productivity while preserving privacy.

From an architectural perspective, geolocation systems may be divided into two types: “Active” and “Passive”. An example of an active system would be one that gathers data from APs – as they report measurements about RF transmissions between themselves and mobile devices – and uses this data to track these mobile devices. Simple mobile transmitters, combined with active geolocation systems, are well suited for inventory management and programs to monitor and secure objects and assets. People, however, may not prefer to be tracked like objects or assets while roaming the halls and rooms of indoor buildings and campus structures [14]. A compromised active geolocation system could actually facilitate a data or even physical personal attack, as an intruder could watch – on-screen – from a distance and wait for a target to move to a vulnerable location. Plus, any residual tracking records from the software could be analyzed for patterns or other variables that infringe upon privacy norms and regulations. Active systems must be highly secured and precisely engineered in order to guarantee the safety and security of users. Further, from a practical perspective, pure active systems alone do not satisfactorily address the problem of disconnected operation, although they can provide high levels of geolocation accuracy [2].

A passive software geolocation system is a functional as well as ethical alternative to active systems. In passive systems, the geolocation protocol and data are publicly offered, and device-resident processes are responsible in the end for interpolating location. GPS is a passive system. Architectural challenges associated with passive systems include optimum formats for data, synchronization and broadcast intervals, and logical signal differentiation – from the perspective of limited devices. A passive geolocation system provides open infrastructure, anonymously broadcasting location-derivable information and inherently accommodating privacy.

2. DEVELOPMENT

2.1 Conceptualizing an Indoor Geolocation System

2.1.1 Assessing Wireless Geolocation Metrics and Methods

As previously discussed, a number of traditional technologies that assist geolocation are not available for indoor wireless applications. Additionally, systems that require specialized equipment – while able to mitigate the need for a reference database – are often discouraged in favor of more manageable, software-only geolocation solutions which still satisfy performance and privacy requirements. A passive indoor geolocation system requires devices themselves to contain referential data, particularly if some functionality is to be provided by the handheld application during disconnected operation. Such a portable database system can be optimized for a fingerprinting approach, whether RSS or another metric is chosen.

In wireless location fingerprinting, the reference database is a set of averaged wireless signal measurements taken at fixed points throughout a building. Each location must exhibit measurable and describable, time-adaptable wireless signal differentiation, mostly involving signals from multiple APs. An example of a fixed point would be “the doorway to Room 101” of a structure. RSS measurements of all visible APs can be recorded in a database over enough time periods to create a reference “fingerprint” for that point. The exact number of required samples per sample point is a question for future research. Compared to a raster or grid type sampling approach, vector techniques that minimize the set of sample points present greater economy in database functionality.

For wireless geolocation, the target database only has one record: the device’s location. Being able to match a device’s RF fingerprint to that of a specific doorway – combined with knowledge of neighboring doorways – could lead to logical assumptions about the device’s location, such as “Inside Room 101” or “Not in this building”. Fingerprinting in this sense generates useful information about the location of a user, making many location-based services possible. Wireless geolocation by fingerprinting happens much the same way as address matching in a geographic information system. Once a set of RSS measurements has been taken, a GIS address matching approach can be employed.

2.1.2 Geolocation and GIS Address Matching

The U.S. Census Bureau utilizes a geocoded reference database system known as TIGER, a vector-based data model for streets and addresses in cities and towns [4]. A look at a TIGER/Line file for a town or area indicates that each line segment (known as street "center-line" modeling) has a defined beginning and ending point, as well as detailed information about the buildings located along each line. In the database, line segments begin at one block (*F_Node*) and end at the next (*T_Node*). Segments are connected into lines to model whole streets. To maintain parity, addresses on the right side of the street are distinguished from those on the left, and a corresponding line segment record in the database contains two ranges of numbers – one for the addresses located on each side.

Figure 2.1: TIGER Street-Line Vector Model for U.S. Census Location Attributes

tgr27013lka.dbf

Tlid	Fnode	Tnode	Length	Fedirp	Fename	Fetype	Fedirs	Cfcc	Fraddl	Toaddl	Fraddr	Toaddr
28107795	1686	1706	0.07678		Main	St	E	A41	301	307	300	304
28099494	2515	2502	0.06931		Main	St		A41	301	399	300	398
28111321	1234	1235	0.02251	N	Main	St		A41	301	399	300	304
28111478	5260	5238	0.02426		Main	St	NW	A41	301	351	300	350
28111479	5238	5229	0.02669		Main	St		A41	301	399	200	350

TIGER is a widely used reference database system for address-matching operations; data tables without geographic location attributes can be plotted on a spatial grid (e.g., a projection or map of a U.S. region) by cross-referencing them with TIGER/line location data. The end result of this geocoding operation is that location attributes are appended to each record in a target database. The process yields four types of matches: full match, partial match, false positive, and unmatchable [4]. With the addition of statistical and other definable rules, match rates can be increased, often with the consequence of a higher error rate. "Check fields" such as zip code help prevent matching errors.

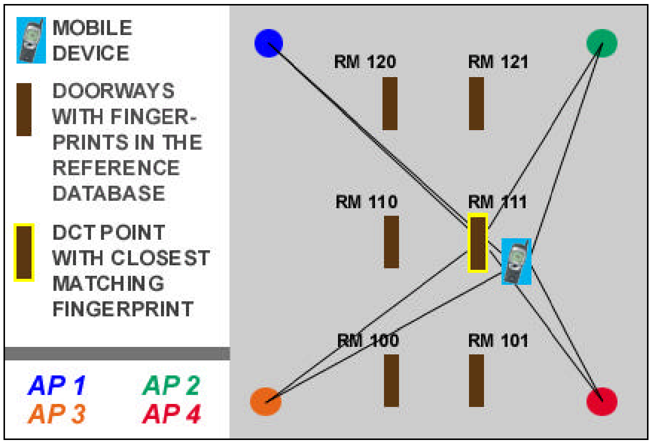
Optimized to rapidly pinpoint either (1) a location, or (2) a location and orientation relative to other locations, address matching is a powerful and compact database operation. In the area of wireless indoor geolocation, such a database has also powerful descriptive qualities. Spatial values defined as sets of polygons connected by a "skeleton" can represent rooms, hallways, courtyards, neighborhoods, and other building or campus structures with a relatively small set of data [8], especially compared to grid or raster files [9]. Thinking of available location-based services as an attribute of location – a GIS concept, it seems natural to extend relevant GIS concepts to other areas of mobile wireless geolocation.

2.2 DCT: An Indoor Wireless Geolocation Infrastructure

2.2.1 Doorway Constellation Topology Described

The concept described in this paper is called Doorway Constellation Topology (DCT). The DCT design assumes that simple device-side processing of RSS and other attributes of RF signals from APs are not sufficient for precision indoor geolocation by triangulation alone. A system of virtual reference points can be developed, first to help adjust signal measurements for anomalies (similar to DGPS as related to GPS), and second to provide portable orientation and location references to mobile devices. Of all available indoor locations, none seem as well suited as room doorways for acting as reference points for indoor location by fingerprinting. DCT takes advantage of the fact that practically every occupied structure has doorways throughout, each with a unique and intuitive designation. With DCT, user position is related to a describable physical location (a doorway) without the requirement of actual location attributes stored in a database – but with inherent spatially intuitive qualities nonetheless.

Figure 2.2: Location Fingerprinting using Doorway Constellation Topology (DCT)



DCT is envisioned to be a passive, publicly available and mobile geolocation system, optimized for the dynamic, and sometimes disconnected, nature of wireless networks. The heart of the system is a database model that merges the characteristics of the wireless network to the physical building or campus without the requirement of an exact floor plan or data-intensive spatial reference grid. With ongoing use, both users and IT staff could easily contribute to the ongoing calibration of the DCT infrastructure by “volunteering” signal measurements from doorways for the central reference database. In its basic form DCT would seem to be suitable for locating a user in a certain part of the building, hallway, or perhaps room. Further database refinements may lead to increased precision.

2.2.2 DCT-enabling a Fingerprinting Reference Database

DCT does not require that doorways have locational attributes stored in a database (e.g., latitudinal and longitudinal coordinates). “Simple” DCT could indicate whether or not a user is in or near a specific room, which is a usable level of detail from the perspective of many software applications. More precise location information can, however, be modeled in a database using DCT combined with an approach similar to TIGER and other geocoded reference systems.

Figure 2.3: Steps in a Theoretical DCT Fingerprint Pattern Matching Application

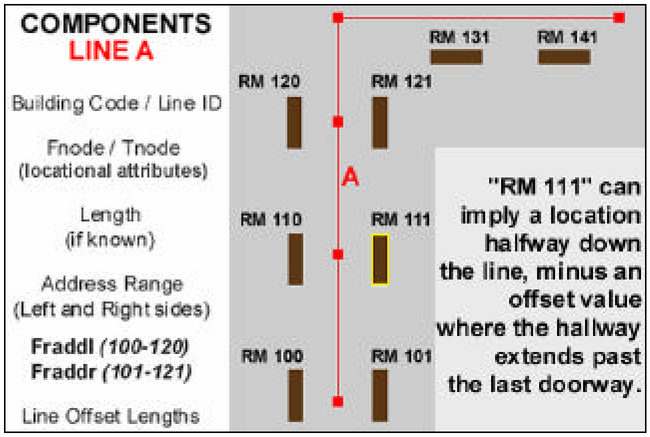
(1) From device, measure signals from each AP (averaged samples)
(2) Generate ratios of measurements from APs for comparison
(3) Rank ratios by AP and classify the resulting fingerprint using a timestamp
(4) Obtain or recall a time-matched reference database for fingerprinting
(5) Perform statistical, interactive, and other pattern matching correlations
(6) Use correlated DCT fingerprints as indicators of proximity and geolocation
(7) Display nearby room numbers to user and/or geocode application requests

Most buildings and campus areas are representable by simple shapes, lines, and points. Currently, combinations of lines and polygons are effectively used in GIS to describe 3D structures in vector databases [8]. In buildings, doorways typically lie in rows or lines. By designating the locations of doorways as points on lines representing hallways, the reference database is simplified. Fingerprint information is tracked for all DCT points, but location attributes can be eliminated from all but doorways that help define the characteristics – start and stop points – of the hallway lines. This abstraction helps make the database more portable than one containing extra details for each reference point.

A fundamental principle behind DCT is that each significant room doorway in a building is uniquely named. It would be unusual, for instance, to have two Room 101's in a single building. Therefore, the label of the doorway combined with the name of the building provides a useful key value in a database table as well as an intuitive indicator of location for users. Room 200 implies a specific place in a building, intuitively distinct from Room 100, which should be on a different floor even if the X-Y coordinates on a two-dimensional plane would be identical. Plus, using room numbers as locational references also minimizes the need for illustrative graphical user interfaces (GUIs), which are more difficult to create on the small screens of many mobile devices. A TIGER-type reference database model – already maximally optimized for spatial representations of outdoor phenomena – can be comprised of DCT reference points contained by hallway line segments, with odd and even sides. The same system adopted by the U.S. government to geocode addresses in towns and cities can be applied almost transparently to indoor geolocation, using doorways and hallways instead.

To compare a DCT fingerprint from the reference database with the instantaneous measurements from a device, a traditional address-matching strategy may be employed, with a few variations. With TIGER and similar systems, a street address is broken down into component parts and compared with *F_Addr* and *T_Addr* – From Address and To Address – ranges for specific street-line segments, until a segment defining the target range is found. For example, 316 Main Street could be located within a segment ranging from 300 to 399. Then, depending upon the semantic rules applied by the matching algorithm, Main Street could be matched with a street spelled as "Main", "Maine", etc. and with a designation of "St" for street (unless street is ignored in the processing). Once a reference street-line segment is found that matches the target with enough probability, "exact" location is interpolated by assuming that point 316 lies about 16% down the line, plus or minus user-definable "offset factors". In DCT, there are no streets and addresses, but fingerprints generated by signal measurements from APs can serve a similar purpose.

Figure 2.4: Determining Spatial Orientation with a DCT Vector Reference Database



DCT-enabled geolocation does not necessarily include knowledge of the location of the APs. Doorway fingerprints alone act as a virtual constellation of reference points. The role of APs in DCT is simply to project their signals like street lamps in a parking lot. Each AP also has a unique networking ID or MAC address (used regularly in routing protocols). It is this AP ID or another key value that adds differentiation to the myriad wireless signals measured by devices. This key AP identifier helps differentiate the AP signal measurements available for a DCT point, and in some form it is present in almost every wireless packet sent to or from a device [13].

In practice, researchers have already developed simplified RF sampling approaches, such as taking signal measurements only in hallways instead in every cell in a floor-covering grid [2,11.] In order for fingerprint measurements to be refined and “calibrated” over time, though, revisits to the same location are necessary, and arbitrary points in hallways – even if marked with paint or tape – seem nowhere near as replicable or intuitive as the thresholds doorways. From the perspective of tying a physical location to a set of records in a reference database, the unique numbering system of doorways enables the abstraction of database key values to remain rooted in the vocabulary of users and administrators. Plus, DCT points provide a regular and reasonably small subset of all available referential sample points to choose from.

In cases when device capacity is minimal, a DCT application could be scaled down to allow just “simple” geolocation by fingerprinting. As mentioned, device location can be usefully correlated relative to rooms in a specific building. If the device has more processing power – and if the DCT infrastructure for a site has been developed into geocoded reference data – then additional precision may be obtained. Portable vector reference databases can be designed for operation of devices disconnected – but within – the wireless network.

Either simple DCT fingerprinting or advanced DCT 3D vector modeling facilitate an increased level of location-aware information services for mobile device users. Any implementation of DCT requires a device-resident database, and strategies that minimize the footprint of this database will be necessary given the capabilities of handheld devices.

As a passive system, DCT would entail each AP broadcasting the DCT points within its wireless range, to be valid for a specific time frame. A device would decide which DCT point broadcasts to accept and store in the portable reference database based upon cell-id and other logical rules. Only DCT points in logical proximity need be included in a database pattern-matching process running on a device. And, once a matching point or points have been found, DCT provides a mechanism for translating them – using vector spatial representations – into usable area maps for users and location-based services. Notably, these maps and their meaning in terms of service delivery and user interactivity would be able to interface seamlessly with existing, outdoor spatial reference systems based upon vector modeling.

3. CONCLUSION

3.1 Summary

This paper discusses various technical approaches to indoor wireless geolocation and assesses them in the framework of developing user-friendly, location-based applications. Designed for the particular challenges of mobile and wireless computing, a lightweight and portable indoor spatial referencing system described as Doorway Constellation Topology is proposed. It is designed to be a common referential platform for indoor spatial modeling as it relates to device location fingerprinting in wireless LANs.

Since doorways are ubiquitous, DCT is meant to adapt and scale to practically any building or campus structure. Of particular benefit is the fact that DCT attempts indoors and on a micro level what geocoded outdoor location systems perform on a macro level. By utilizing a TIGER-type vector reference database, DCT has potential to be virtually interchangeable with outdoor vector-based geocoding applications, such as E-911 and other street-line systems. An address located by E-911 could be correlated to DCT attributes, seamlessly expanding what would be just one identified point into a locational description of what could be a large building or structure. In theory, DCT could be a transparent partner with such outdoor geolocation systems, providing an attractive opportunity for software-only, passive geolocation infrastructure.

In a world where precision indoor wireless geolocation is a highly complicated engineering problem, DCT represents a system of compromises. A DCT fingerprint database, even with vector-based location modeling, represents a compact data model comprised of an intuitively named subset of reference points. And, with ongoing use, DCT contains a convenient mechanism for auto-calibration. Advances in measuring RSS and other metrics will only lead to more effective methods of generating useful RF fingerprints, enhancing DCT accuracy.

3.2 Ongoing Research and Development

Moving forward, several theoretical and practical concerns must be addressed. Future research will focus on implementation questions, performance on mobile devices, and 3D, vector-based spatial modeling. The optimal process must be identified for sampling DCT points and representing fingerprints as time-dependent entities in a compact database. Fast pattern-matching algorithms will need to be found for mobile devices, and results displayed interactively to the user. And more study must be done regarding the ability of doorways alone to logically represent a mobile device's location, with acceptable precision. As a multidisciplinary approach to indoor wireless geolocation, DCT opens several areas of inquiry.

REFERENCES

1. Acampora, A. (2002). *Last mile by laser: Short-range infrared lasers could beam advanced broadband multimedia services directly into homes and offices.* SCIENTIFIC AMERICAN (July), 49-53.

2. Bahl, P. and Padmanabhan, V. (2000). *RADAR: An In-Building RF-based User Location and Tracking System*. Microsoft Research. IEEE INFOCOM 2000.

3. CIO Magazine & Synchrologic (2001). *CIO outlook 2001: Architecting mobility. Ten critical steps in supporting mobile enterprise computing.* Alpharetta, GA: Synchrologic, Inc. www.synchrologic.com

4. Drummond, W. J. (1995). *Address Matching: GIS Technology for Mapping Human Activity Patterns.* APA Journal (Spring), 240-251.

5. Kishan, A., Michael, M., Rihan, S. & Biswas, R. (2001, June). *Halibut: An infrastructure for wireless LAN location-based services.* Stanford: Stanford University.

6. Hassan-Ali, M & Pahlavan, K. (2002). *A new statistical model for site-specific indoor radio propagation prediction based on geometric optics and geometric probability*. IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, 1(1), 112-124.

7. Kuikka, P (1999). *Wideband radio propagation modeling for indoor geolocation applications.* Seminar on telecommunications technology. Helsinki, Finland: University of Helsinki, Department of Computer Science.

8. Lee, J (2001). *A Spatial access oriented implementation of a topological data model for 3D urban entities.* The Ohio State University, Department of Geography.

9. Lo, C.P. and & Albert K. W. Yeung (2002). *THE CONCEPTS AND TECHNIQUES OF GEOGRAPHIC INFORMATION SYSTEMS.* Upper Saddle River, NJ: Prentice-Hall, Inc.

10. Pahlavan, K., Latfa-aho, M & Ylianttilia, M. (2000). *Comparison of indoor geolocation methods in DSSS and OFDM wireless LAN systems.* IEEE VTC 2000

11. Pahlavan, K. & Li, X. (2002). *Indoor geolocation science and technology: Next-generation broadband wireless networks and navigation services.* IEEE COMMUNICATIONS MAGAZINE (February), 112-118.

12. Prasithsangaree, P., Krishnamurthy, P. & Chrysanthis, P.K. (2001). *On indoor position location with wireless LANs*. Telecommunications Program & Dept. of Computer Science, University of Pittsburgh. Pittsburgh, PA.

13. Schiller, J. (2000). MOBILE COMMUNICATIONS. London: Pearson Education.

14. Smailagic, A, Siewiorek, D., Anhald, J., Kogan, D., Wang, Y. (2000). *Location sensing and privacy in a context aware computing environment*. Institute for Complex Engineered Systems, Carnegie Mellon University, Pittsburgh, PA.

15. Wallbaum, M. (2002). *Wheremops: An indoor geolocation system*. Department of Computer Science, Aachen University of Technology. Aachen, Germany. IEEE PIMRC.

16. Waters, J. K. (2001). *Special report: Wireless development.* APPLICATION DEVELOPMENT TRENDS (March), 32-35.

17. Zhao, Y. (2002). *Standardization of mobile phone positioning for 3G systems.* IEEE COMMUNICATIONS STANDARDS REPORT (July).

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