WPI Precision Personnel Locator System: Automatic Antenna Geometry Estimation

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BIOGRAPHY

Mr. Benjamin Woodacre is a Ph.D candidate in Electrical and Computer Engineering at WPI. Since completing his BS and MS degrees at WPI in 2002 and 2004, he has served as a research assistant in the WPI Convergent Technology Center sponsored by the NIJ/DOJ on the topic of precision personnel location. His MS work examined variation of TDOA location algorithm performance as a function of geometry, and his Ph.D. research concerns techniques for antenna geometry auto-calibration.

Dr. David Cyganski is professor of Electrical and Computer Engineering at WPI where he performs research and teaches in the areas of linear and non-linear multidimensional signal processing, communications and computer networks, and supervises the WPI Convergent Technology Center. He is an active researcher in the areas of radar imaging, automatic target recognition, machine vision and protocols for computer networks. He is coauthor of the book *Information Technology: Inside and Outside*. Prior to joining the faculty at WPI he was an MTS at Bell Laboratories and has since held the administrative positions of Vice President of Information Systems and Vice Provost at WPI.

Dr. R. James Duckworth is an Associate Professor in the Electrical and Computer Engineering department at WPI. He obtained his PhD in parallel processing from the University of Nottingham in England. He joined WPI in 1987. Duckworth teaches undergraduate and graduate course in computer engineering focusing on microprocessor and digital system design, including using VHDL and Verilog for synthesis and modeling. His main research area is embedded system design. He is a senior member of the IEEE, and a member of the ION, IEE, and BCS and is a Chartered Engineer of the Engineering Council of the UK.

Dr. William R. Michalson is a Professor in the ECE Department at the WPI where he performs research and teaches in the areas of navigation, communications and computer system design. He supervises the WPI Center for Advanced Integrated Radio Navigation (CAIRN). His research focuses on the development, test, and evaluation of systems, which combine communications and navigation. He has been involved with navigation projects for both civilian and military applications with a special emphasis on navigation and communication techniques in indoor, underground or otherwise GPS-deprived situations. Prior to joining the faculty at WPI, Dr. Michalson spent approximately 12 years at the Raytheon Company where he was involved with the development of embedded computers for guidance, communications and data processing systems for both space borne and terrestrial applications.

ABSTRACT

This paper describes the latest developments in the Worcester Polytechnic Institute (WPI) Precision Personnel Location (PPL) system. The RF-based PPL system is being developed for tracking of first responders and other personnel in indoor environments. The system assumes no existing infrastructure, no pre-characterization of the area of operation and is designed for spectral compliance. This paper concentrates on describing ongoing work towards an accurate and automatic method for determining the coordinates of the receiving stations of our location system within a local coordinate system. The accuracy of the receiving station locations is a prerequisite for meaningful and accurate location estimates for personnel, which have demonstrated sub-meter accuracies in realistic multipath environments using manually surveyed receiver positions. This paper documents our approach to receiving station geometric auto-configuration (GAC), the algorithms currently employed, and presents the results from a number of experimental tests. This paper is also one of the first documenting results from our new 150 MHz bandwidth system.

INTRODUCTION: WPI PRECISION PERSONNEL LOCATOR SYSTEM

Previous papers by the authors [1-6] have described the general system architecture, precision location approach, hardware design challenges, signal structure, and experimental results paralleling the development and refinement of the system's hardware realization. Figure 1 depicts an artist's rendition of the PPL concept.

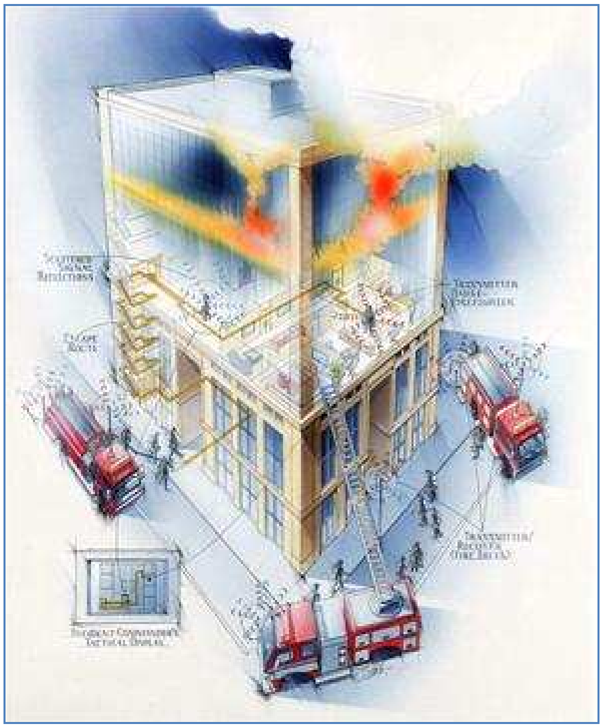

Figure 1 - PPL concept illustration

The goal of the system is to provide a robust real-time tracking solution which requires zero pre-installed infrastructure. To be tracked, firefighters and other emergency personnel each carry a transmitter emitting a multi-carrier wideband (MC-WB) signal [4], which is sensed at receiving stations fixed upon emergency response vehicles. Upon arrival, the receiving stations form an ad-hoc network and establish a local coordinate system.

Given the receiving stations' positions within the local coordinate system, the signals collected at each station are transferred to a central location where the relative positions of the transmitters within the coordinate system are estimated. These estimates are then conveyed to command-and-control software in the hands of the incident commander. Accumulation of track information for many transmitters has the effect of providing the incident commander with valuable information on building layout to assist with exit guidance or search and rescue operations. Efforts are also underway to integrate additional information into the incident commander's display to enable monitoring of personnel physiological status and ambient environmental conditions.

EXPERIMENTAL LOCATION TESTS

Publications [2] by the authors have presented location testing results from a 60 MHz RF system and from a new 150 MHz wideband system [1]. The results of these tests are summarized here in Table 1; all results involve location of a transmitter inside the building by antennas placed outside of it, except in the Atwater Kent indoor case where the receiving antennas were also placed inside the building. The Kaven Hall test location is brick and steel-beam construction and houses a geotechnical lab on the WPI campus; the Atwater Kent location is an indoor-to-indoor test centered around an undergraduate laboratory, passing through steel-studded walls and under metal-corrugated ceilings; and the Campus Ministry location is a typical wood-construction three-story residential structure complete with furniture and metal appliances in the kitchen.

Table 1 - Location Testing Mean Absolute Errors

Test Location	Error	Bandwidth
Kaven Hall	0.37m	60 MHz
Atwater Kent, indoor	0.71m	60 MHz
Atwater Kent	1.08m	60 MHz
Campus Ministry 1st fl.	0.59m	60 MHz
Campus Ministry 2nd fl.	0.72m	60 MHz
Campus Ministry 1st fl.	0.72m	150 MHz
Campus Ministry 2nd fl.	0.30m	150 MHz

The errors in Table 1 provide a reference for the desired accuracy of the antenna coordinates in the GAC process in a realistic deployment. Other experiments utilizing the new 150 MHz RF hardware have been conducted for the purposes of testing GAC in three situations with increasingly difficult multipath conditions: outdoor, indoor with direct line-of-sight, and around-building antenna placements. All results presented in this paper have been generated from data collected with this new hardware and spectral allocation.

GEOMETRIC AUTO CONFIGURATION

Geometric auto configuration (GAC) is the process by which our location system, in an unattended fashion, automatically determine the locations of the receiving stations. The GAC process can be divided into two parts. The first part is the accurate determination of the relative locations of the receiving stations, which is the primary challenge considered in this paper and is solely concerned with coordinate system location accuracy. The second part of GAC concerns the mapping of the antenna configuration in a meaningful way within the context of the area of operations and conforming with common conventions of relative and absolute position used by response personnel. For example, at residential fires in Worcester, Massachusetts, firefighters typically label the four sides of the building A, B, C, and D, proceeding clockwise relative to the incident command post. It is conceivable that position and orientation information for the receiving antenna arrays by virtue of being mounted on fire trucks could be obtained via GPS, however to satisfy the target system accuracy, such fixes would consistently need to achieve sub-meter accuracy. Such partial location and orientation information would aide the GAC process in narrowing the solution space for array locations and orientations and thus reduce computation time, but can not obviate it.

To accomplish GAC, each of the *N* receiving stations are equipped with a MC-WB transmission capability. Upon arrival at an incident, the stations in turn transmit the multi-carrier signal while all others receive it from their deployed locations. The receiving stations simultaneously record the signal associated with each transmitter resulting in N^2-N received signals captured in total. At each transmit station, the transmitter RF input may be synchronously captured by the unused receiver. This synchronous signal capture allows measurement of the transmitter's time offset at that moment so that subsequent elimination of such offset in software is possible.

From the ensemble of signals collected in this process, the solution for the antenna configuration may be prosecuted. As the problem of GAC and transmitter location are inherently similar, two possible avenues of solution arise: one based on our group's original approach to transmitter location [4], and the second based on our novel, as yet unpublished, multi-lateralization technique. The first approach involves estimation of the direct path propagation distance and elimination of transmitter offset via time-difference of arrival (TDOA), followed by direct solution for transmitter position given the estimated TDOAs for all receivers. The second approach is a single algorithm which uses a TDOA-like multi-lateralization technique to directly solve for the transmitter location. While the first technique was ultimately dropped in favor of the second technique for individual transmitter location, the first approach remains viable for GAC, due to the more forgiving outdoor radio channel. While we have pursued both solution avenues, our implementation of the second is not ready for full presentation, and the first approach has yielded appreciable results. The following sections detail this approach, herein named TOA-MDS, which consists of super-resolution TOA (range) estimation to determine the set of inter-antenna distances, and the method of multidimensional scaling (MDS) to translate those distances into three-dimensional antenna coordinates.

RANGING ALGORITHM

The MC-WB signal consists of a collection of *N* discrete, unmodulated sub-carriers, each of negligible bandwidth, spread throughout a bandwidth of operation *B* Hz, and, as required for our range estimation process, spaced at *B/N* Hz [6]. An example of our current multi-carrier signal (at baseband frequencies) viewed on a spectrum analyzer can be seen in Figure 2, where approximately 100 sub-carriers are spread over a 150 MHz bandwidth. The carriers are spaced evenly except where deletions have been made to avoid interfering with existing services in our 550-700 MHz band.

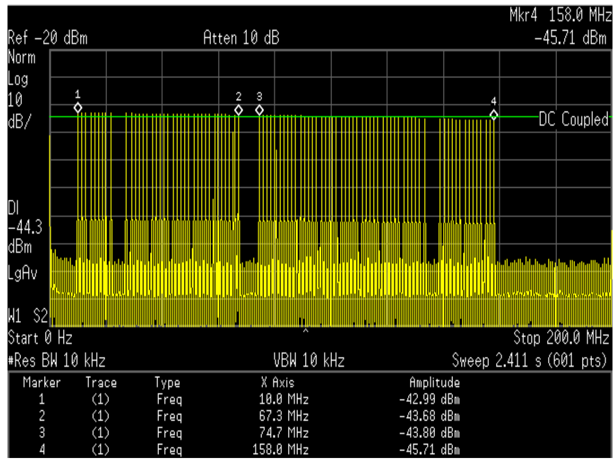

Figure 2 - MC-WB baseband spectrum

To utilize super-resolution ranging for the purposes of GAC, all superfluous hardware effects, signal delays, and timing offsets are eliminated to allow accurate estimation of the channel response and thus propagation distances of the direct and indirect signal paths between transmitter and receiver. In addition, an extrapolation process is utilized to fill in the sub-carrier gaps and virtually extend the bandwidth of our signal by 30%, which both directly benefit the range estimation process in creating a large span of evenly-spaced carriers.

The typical GAC scenario for neighboring antennas has been found to be a suitable application for the super-resolution technique, as the channel does not experience the attenuated direct path and near-multipath [3] effects of an indoor channel. Range estimation proceeds as described in [7] by forming a Hankel matrix obtaining, for each antenna pair, a list of signal solutions each described by a propagation distance and signal strength. From each list of signal solutions the signal corresponding to the direct path must be selected. Given the low-multipath nature of the outdoor environment used for GAC, the best decision metric to find the direct path signal is to choose the strongest one.

One source of error that we have experienced in range estimation relates to distortion of range estimates due to antenna effects. During the design phase for our new antennas operating in the 550-700 MHz band, we paid special attention to limiting the variation of phase response as a function of antenna angle at the expense of impedance matching. This phase variation modeled as a first-order effect corresponds to a time delay, such that an antenna designed badly in this aspect would exhibit an angle dependence at the output of our range estimator. These effects unsurprisingly worsen for variation of elevation angle as compared to azimuth. It is a great benefit that antennas permanently mounted on the same vehicle have their configurations known, as they are the antennas with the highest potential for range distortion.

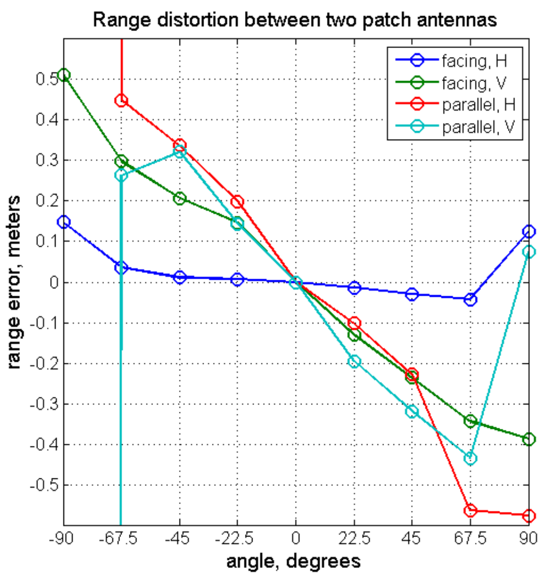

Figure 3 - Patch antenna range distortion

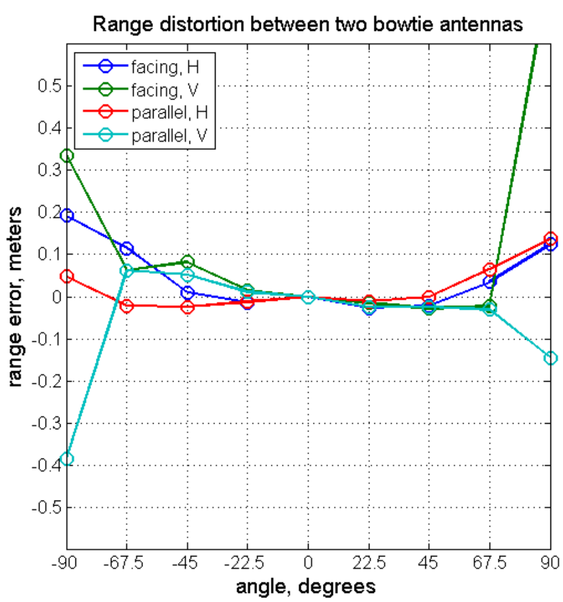

Figure 4 - Bowtie antenna range distortion

Figure 3 shows the experimentally determined range biasing effect between two of our UHF patch antennas relative to $0°$ for variation of azimuth and elevation angle. Range bias worsens when the antennas are edge-on (labeled "parallel") and in elevation (designated with "V") tests. When the patch antennas go edge-on to each other, low signal levels play a stronger role effecting range distortion. This range distortion effect is clearly less pronounced for the case of our wideband dipole, or "bowtie" antenna as seen in Figure 4.

MULTIDIMENSIONAL SCALING

The technique of multidimensional scaling is used to determine low-dimensional representations of high-dimensional data [9]. MDS is used in a variety of disciplines to simplify data with many parameters to a lower number of parameters which best fit, by some error metric (e.g., least squares) the original data. In MDS, such high-dimensional input data are the set of estimated inter-antenna distances between N antennas, contained within an NxN symmetric distance matrix:

$$D = d_{ij}$$

where d_{ij} is the distance between the ith and jth antennas. With the 3xN matrix X containing the column vectors of true receiver coordinates, direct MDS relates the inner product of the desired antenna coordinate vectors with the squared distance matrix via an eigenvalue decomposition:

$$X^T X = -\frac{1}{2} C D^2 C = V \Lambda V^T$$

where C is the centering matrix. This direct solution works perfectly with noiseless data, but degrades in performance in the presence of errors in the distances in D. Our implementation utilizes an iterative gradient-descent version of the MDS process which allows weighting of entries in D, missing data (signified by zero weight), and an initial solution guess used as the starting point of iteration. Weighting is accomplished via a weighting matrix W, whose entries contain the desired weight for the corresponding entries in D.

In our implementation, MDS is initialized with a circular configuration of receivers in two dimensions and a distance-based weighting scheme assigning weight inversely proportional to the squared distance between receivers in this initial guess. Antennas installed on the same vehicle do not require range estimation as their configurations are known, and thus their separations are inserted directly into D and higher relative weighting coefficients into W. As a substitute for our circular initialization, it is feasible that such position fixes as obtained from GPS could be used as initial receiver coordinates to reduce the number of iterations required to find a solution.

Upon termination of the MDS iterations, the resultant set of coordinates is arbitrarily oriented in three dimensions. MDS preserves the ordering of the receivers, such that the receiver whose estimated antenna separations are listed in the first column of the distance matrix is also the first receiver listed in the matrix of estimated receiver coordinates. This correspondence allows rough alignment of the coordinate system to a map given knowledge of the directions of gravity and magnetic north and absolute position based on an outdoor GPS fix.

Finally, the capability for missing data in *W* and the redundancy in some of the information in *D* allows convergence of the iterative MDS solution, given no input errors, when only as few as 32 out of 120 unique distances in an array of 16 antennas are known. These 32 distances correspond to the first two super- and sub-diagonals in *D*, and are the ranges to the nearest and next-nearest neighbors on each side to each antenna. This convergence given only partial information can offer a significant benefit, as the necessity for estimating ranges accurately to antennas which are further away and likely to have an occluded line of sight or high amounts of multipath due to intervening structures, which are therefore likely to have the highest ranging errors, is greatly reduced.

GAC TESTING RESULTS

A previous paper [1] has shown location results with a 150 MHz wide ranging signal centered at 625 MHz. The following sections present test results using the same hardware setup to collect the ensemble of signals between every possible pair of receiving antennas. The tests' goal is to estimate the configuration of the receiving stations with an RMS error less than or equal to the desired transmitter location error of 0.3m (1 foot) of our system. The errors are computed relative to the hand-measured configurations of the receiving antennas. The RMS location error is expressed as

$$err = \sqrt{\frac{1}{N}\sum_{i}(\hat{x}_i - x_i)^2 + (\hat{y}_i - y_i)^2 + (\hat{z}_i - z_i)^2}$$

where N is the number of antennas, and (x_i, y_i, z_i) are the coordinates of the i^th receiver, and $(\hat{x}_i, \hat{y}_i, \hat{z}_i)$ are estimated coordinates for the i^th receiver. Also based on the known coordinates are truth values for the inter-antenna ranges. RMS ranging error is measured as:

$$err = \sqrt{\frac{1}{N}\sum_{i}(\hat{r}_i - r_i)^2}$$

Due to the ability of our MDS method to form a coordinate solution with incomplete data, the following results present errors as a function of neighbor distance or proximity along the perimeter. Results generated for a particular neighbor distance only included data between antennas when they were a proximity equal to or less than the stated neighbor distance. Figure 5 illustrates the concept of neighbor distance measured between two groups of antennas (in black) whose configurations are known.

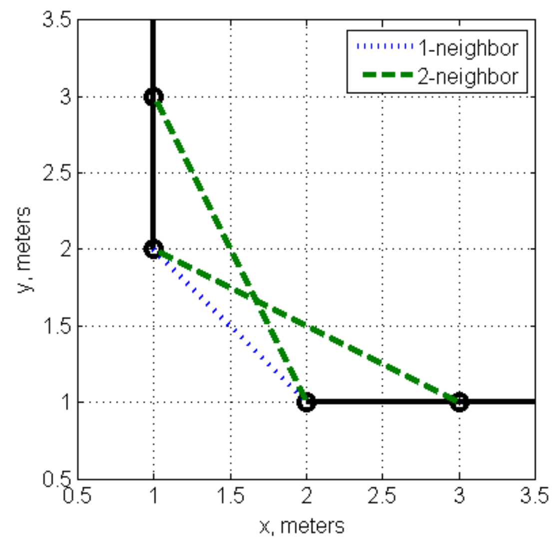

Figure 5 - Illustration of neighbor distance

Results from the two steps of the TOA-MDS process are presented and analyzed individually in the following sections in three scenarios: completely outdoor, indoor un-obscured line of sight, and around-building. Additionally, some ranging errors are completely ignored in the antenna location results due to the assumption that antennas part of the same array will know their inter-antenna distances exactly. Figure 6 shows the rectangular antenna layout used for the outdoor and unobstructed indoor testing and the grouping of arrays.

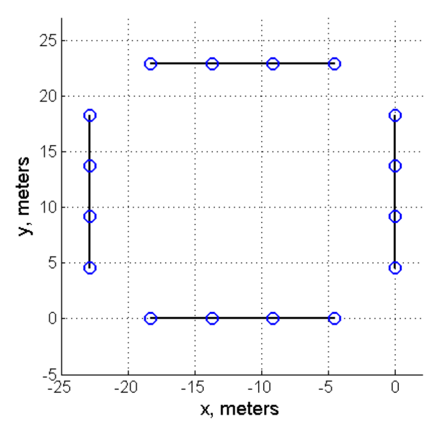

Figure 6 - Antenna layout for indoor & outdoor tests

OUTDOOR TESTING

Figure 7 shows ranging results for an unobstructed outdoor test collected using bowtie antennas. As expected, RMS ranging error is low everywhere, and increases when ranging to more distant antennas at higher values of neighbor distance. Figure 8 shows the resulting MDS processing which gives RMS antenna location of less than one foot for all values of neighbor distance.

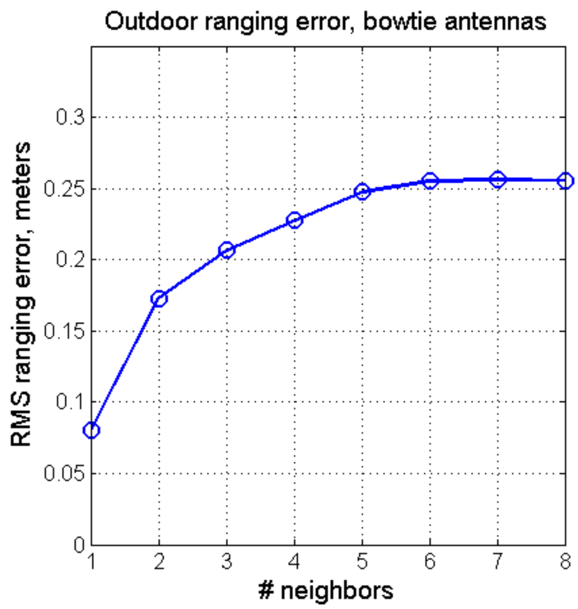

Figure 7 - Outdoor ranging error

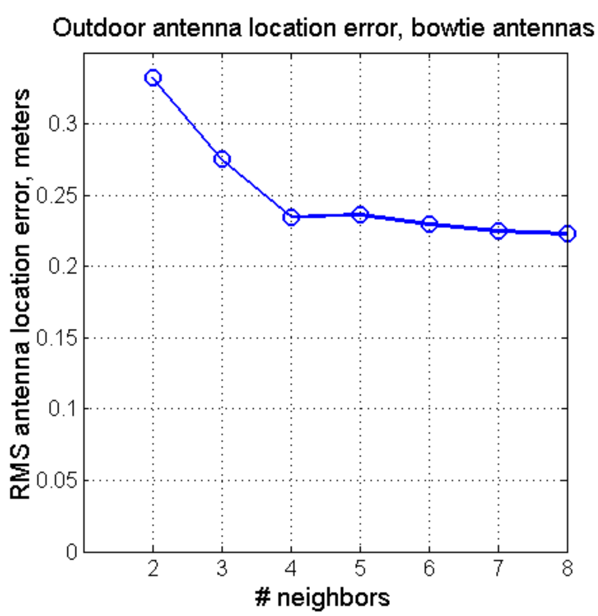

Figure 8 - Outdoor MDS error

INDOOR TESTING

Indoor testing serves as an intermediate step between outdoor testing and around-building testing. This testing took place indoors, in a large function hall in the configuration of Figure 6 with direct line of sight between all antennas and little clutter. For low values of n, the patch antennas see neighbors at extreme angles and thus suffer from range distortion. The bowtie antennas fare better than the patch antennas, requiring more data than the outdoor case to achieve 0.2m RMS location error at n=5.

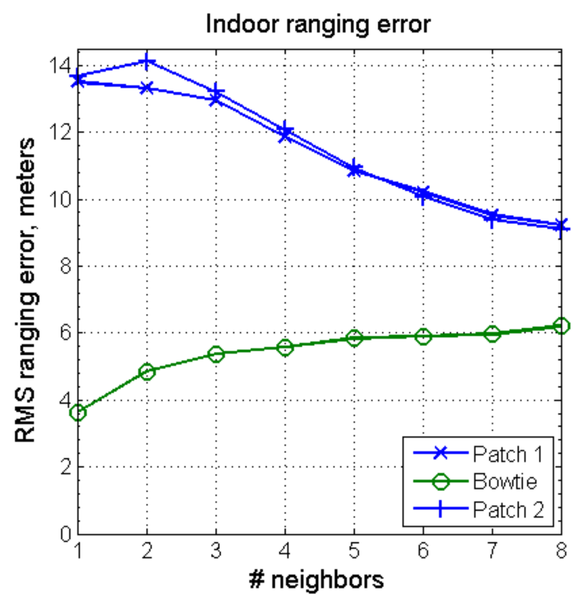

Figure 9 - Indoor ranging results

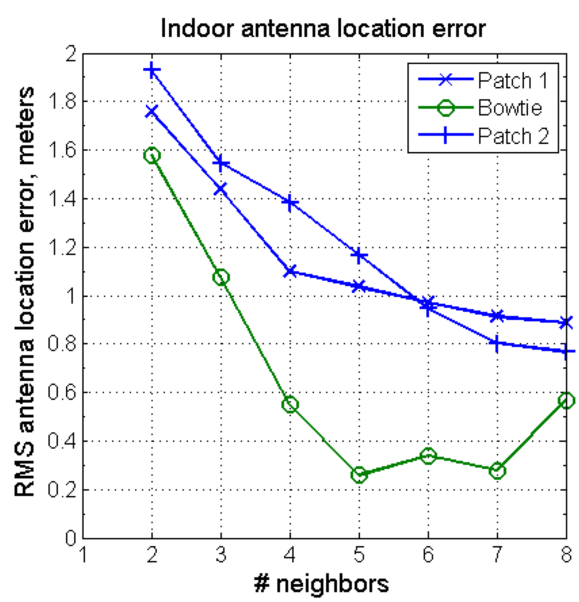

Figure 10 - Indoor MDS results

AROUND-BUILDING TESTING

Around-building testing was performed at both the Kaven Hall location and Campus Ministry locations cited in previous sections using only bowtie antennas. At lower values of neighbor distance, the ranging and resulting position errors are lower, reaching a minimum error of 0.8m at n=3. The Kaven Hall test suffered from poor geometry due to coverage on only three sides of the building.

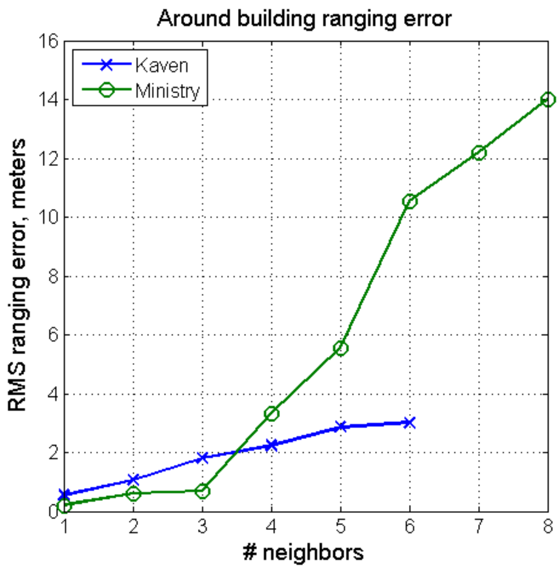

Figure 11 - Around building ranging results

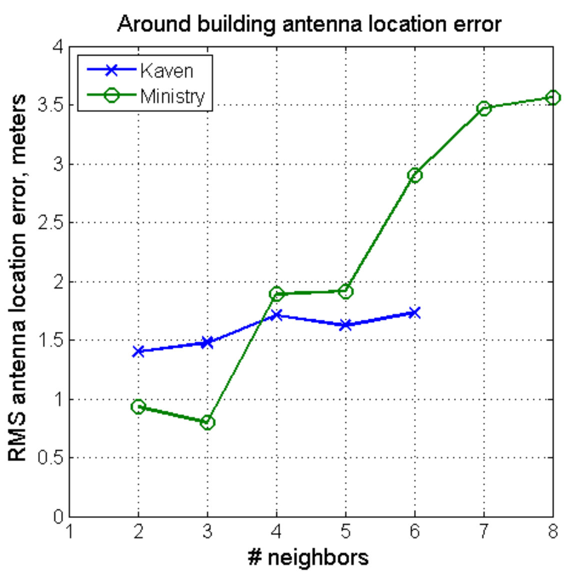

Figure 12 - Around building MDS results

CONCLUSIONS

This paper documents a working implementation of geometric auto configuration based on range estimation and multidimensional scaling. It has been shown that GAC is capable of providing near- or sub- meter antenna location performance in situations with suitable receiver geometry, even given partial data and antenna pattern effects

ACKNOWLEDGMENTS

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