Broadband Ultrasonic Location Systems for Improved Indoor Positioning

Mike Hazas and Andy Hopper

Abstract—Ultrasonic location systems are a popular solution for the provision of fine-grained indoor positioning data. Applications include enhanced routing for wireless networks, computer-aided navigation, and location-sensitive device behavior. However, current ultrasonic location systems suffer from limitations due to their use of narrowband transducers. This paper investigates the use of broadband ultrasound for indoor positioning systems. Broadband ultrasonic transmitter and receiver units have been developed and characterized. The utilization of these units to construct two positioning systems with different architectures serves to highlight and affirm the concrete, practical benefits of broadband ultrasound for locating people and devices indoors.

Index Terms—Location-dependent/sensitive, pervasive and ubiquitous computing, support services for mobile computing.

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1 INTRODUCTION

In the past 15 years, there has been an increasing research focus on developing systems which can perform location sensing. Positioning data of nodes can be used in wireless network deployments to improve dynamic routing or to allow location-stamping of sensor data. By additionally tracking users, location systems also enable a diverse range of context-aware applications, allowing devices to more effectively serve the people using them.

The Global Positioning System (GPS) allows mobile receiver units to compute their position by measuring radio signal times-of-arrival from satellites [1]. Typical accuracies are within a few meters, but GPS performance is seriously hampered indoors. To address this shortcoming, a number of dedicated indoor location systems have been developed. All involve gathering data by sensing a real-world physical quantity and using it to calculate or infer a position estimate. Some of the earliest systems rely upon periodic infrared light pulses sent between transmitter and receiver units [2], [3], [4]. The infrared signal uniquely identifies the transmitting unit and, using the known location of the fixed units in the system, the position of mobile units can be estimated with room-scale granularity. More recently, location systems based upon radio signals have been introduced. Some utilize visibility or signal strength measurements of wireless LAN access points [5], while others rely upon specialized tags and infrastructure to perform radio signal time-of-flight measurements [6]. Both types of systems have typical accuracies of three meters or more.

In contrast, *fine-grained* location systems are capable of supplying positioning information with centimeter-level accuracy, which can be used to enhance existing applications as well as enable new ones. A number of fine-grained location-aware applications exist for workplace, home, and public spaces. Examples include moving maps, mobile desktop control, follow-me teleconferencing and multimedia streaming, activity annotation, ubiquitous user interfaces, augmented reality, indoor environmental control, phone call forwarding, monitoring and support systems for the elderly, and museum tour guides.

Ultrasonic location systems have proven to be a relatively simple, effective solution for fine-grained indoor positioning. However, existing ultrasonic location systems for mobile computing all utilize narrowband ultrasound, forcing compromises in a number of aspects of system performance.

This paper explores the use of broadband ultrasound as the basis for fine-grained location sensing. First, previous fine-grained ultrasonic location systems are reviewed and their common limitations identified. Broadband ultrasonic transmitter and receiver units appropriate for use in prototype indoor positioning systems are then described and characterized. A suitable spread spectrum signaling method is outlined and its capacity for ranging is evaluated. This paper then reports experimental results taken using a polled, centralized location system and a privacy-oriented location system. The performance analysis of the two systems allows general conclusions to be drawn about the benefits of broadband ultrasonic location systems.

2 RELATED WORK AND MOTIVATION

A variety of fine-grained indoor location sensing solutions exist for mobile computing. In the *HiBall* system, user-worn lateral effect photo diodes sense arrays of flashing infrared LEDs mounted in the ceiling [7]. Ultra-wideband radio location systems developed by Ubisense Ltd. utilize receivers deployed in a building to track users carrying small tags which emit ultra-wideband signals [8]. The *TRIP* system employs computer vision techniques to track 2D circular bar code tags on users and devices [9].

Although highly effective, fine-grained infrared and ultra-wideband systems employ specialized hardware and

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are currently relatively expensive for many mobile computing scenarios. Computer vision-based approaches which use commodity cameras are potentially lower cost, but they have yet to be deployed on large scales. Thus, their true cost has not been assessed and their ability to perform wide-area tracking of many people and devices in everyday environments has not been confirmed.

A number of other research efforts have been directed toward ultrasonic location systems. Ultrasonic transducers are relatively inexpensive, and their signals typically have lower processing requirements than the solutions mentioned above, resulting in simple, lower-cost systems which have proven to be effective for wide-area fine-grained positioning indoors.

2.1 Ultrasonic Location Systems

In the *Bat* system [10], users wear small badges which emit an ultrasonic pulse when radio-triggered by a central controller. The system determines pulse times-of-flight from the badges to a network of receivers on the ceiling and calculates the 3D positions of the badges using a multilateration algorithm. The system yields location information with an accuracy of approximately 3 cm and an aggregate location update rate of 150 Hz is theoretically possible.

The *Cricket* system [11] employs *beacons* distributed throughout a building which each send an RF signal describing the surrounding space while simultaneously sending an ultrasonic pulse. The beacons broadcast at random times in order to minimize signal collisions. Devices called *listeners*, carried by mobile users, receive the RF and ultrasonic signals and calculate their approximate distance from the beacon using time-of-flight methods. The first implementation of the system could localize users to within an area of about one square meter, but by using a greater density of beacons, the authors were able to achieve between 5 and 25 cm accuracy [12]. Since 25 distance samples were gathered from each beacon to minimize the effects of reflections and ultrasonic noise, a single location update would take an average of over 5 seconds to produce. The listeners can independently locate themselves, avoiding the potential compromises of user privacy involved with centralized systems.

Similarly, Randell and Muller describe a system [13] which allows wearable and mobile computers to autonomously compute their position. Four ultrasonic transducers are placed at the corners of a square on the ceiling and are wired to a controller. The controller sends a radio trigger and then issues an ultrasonic pulse from each of the four transducers in succession. A mobile receiver unit, synchronized by the radio trigger, measures the ultrasonic pulse times-of-flight from which it estimates its location with 3D accuracies between 10 and 25 cm. The update rate of the system is several hertz.

2.2 Limitations of Narrowband Ultrasonic Location Systems

The above three systems all utilize narrowband ultrasonic transducers for their ranging measurements. Three inherent limitations arise because of this:

1. **Single-user access.** If multiple colocated transmitters send signals at the same time, the signals can interfere with one another, corrupting reception.
2. **Lack of identification encoding.** Narrowband systems characteristically have slow data rates, which make it nearly impossible to encode a unique identifier in the short-duration ranging signal; thus, it is difficult for a receiver to distinguish between the signals from different tags.[1]
3. **Noise sensitivity.** The systems exhibit poor performance in the presence of ultrasonic noise.

The ultrasonic location systems described above avoid the first problem by attempting to ensure that colocated transmitters send their signals one-at-a-time. This solution comes at the expense of a slower update rate; allowing only one transmitter to send at a time constrains the number of location updates possible for a given time interval.

The second problem is often addressed by using a wider bandwidth technology, such as radio or infrared, to indicate the identification of a transmitting unit. However, providing a dedicated communications channel for this purpose increases system complexity, requires more static infrastructure, and raises the power consumption of the mobile devices.

The third problem has not been addressed. Ultrasonic noise is created through peoples' everyday actions. Examples include the clink of a pencil dropping onto a desk, the clacking of someone typing on a computer keyboard, or the rustling of a bag of potato chips being opened. These sounds occur frequently in typical indoor environments. For the duration of such an occurrence, the above ultrasonic location systems are prohibited from generating accurate, up-to-date position estimates for mobile units colocated with the noise source.

It is proposed that broadband transducers and spread spectrum signaling techniques be used to overcome these limitations. The aim of the research presented in this paper is to identify and characterize the practical benefits of broadband ultrasound for indoor location systems.

3 DEVICE DESCRIPTION AND CHARACTERIZATION

Prototype broadband ultrasonic transmitters and receivers, collectively referred to as *Dolphin* units, have been developed. This section describes the design and characterization of the Dolphin prototypes. It is shown that channel bandwidth, as well as the transmitter and receiver angular sensitivity patterns, justify the use of the Dolphin prototypes for exploration of the capabilities of broadband ultrasonic location systems.

It should be noted that the Dolphin units were designed to facilitate *flexibility*, in order to fully gauge the potential of the new technology. Thus, the devices have not been optimized for size or power consumption, and signal analysis and generation are performed externally. However, optimizing the designs to make the units small, self-contained, wireless, and battery-powered is feasible, and the modifications needed in order to accomplish this are set out in Section 5, alongside the discussion of Dolphin location system implementations.

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[1] Although the Bat system, which uses a differential-phase modulation technique, allows up to three tags to transmit simultaneously [10], it still cannot uniquely identify tags from their ultrasonic ranging signals alone.

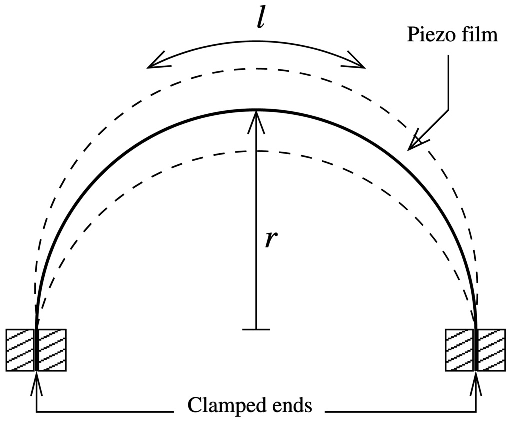

Fig. 1. Operation of a clamped cylindrical piezopolymer transducer [20].

3.1 Transducer Selection and Mounting

The narrowband transducers typically used in ultrasonic location systems rely on piezoelectric ceramics as their sensing elements. These kinds of transducers are inexpensive, small, rugged, and have a high sensitivity. However, they are highly resonant and, in most cases, have a usable bandwidth of less than 5 kHz.

Electrostatic transducers, on the other hand, possess high sensitivity and extremely wide bandwidth. However, they are not very rugged and are expensive, making their deployment on a large scale prohibitive.

Certain synthetic polymer films have piezoelectric properties [14] and are known as *piezopolymer films* or simply *piezo films*. These piezo films, most notably polyvinylidene fluoride (PVDF), have been applied as ultrasonic transducers in hydrophone applications, and for high frequency (greater than 200 kHz) medical imaging and nondestructive testing [15], [16], [17], [18]. Piezo film transducers are small, inexpensive, more rugged than electrostatic transducers, and have a wide frequency bandwidth.

Although there are off-the-shelf piezo film devices available which have appropriate bandwidth characteristics for ultrasonic location, these packages tend to be too bulky for application in mobile computing scenarios. Thus, it was necessary to create a piezo film transducer which is small and unobtrusive, but still has a bandwidth and radiation pattern appropriate for indoor location systems.

A piezo film ultrasonic transducer for air ranging has been designed by Fiorillo [19], [20] and further characterized by Wang and Toda [21] and Toda and Tosima [22]. It consists of a small, rectangular piece of piezo film mounted along two of its edges to form a half-cylinder. As depicted in Fig. 1, the design works by virtue of the fact that the ends of the piezo film are firmly clamped. Any change in the radius r of the hemicylinder can be seen as a change in the length l of the piezo film, since $l = \pi r$. Due to the piezoelectric properties of the film, changes in l are approximately proportional to the voltage across the thickness of the film. Thus, the clamped piezopolymer can function in two ways:

1. as a transmitter, when voltages are applied to it, and
2. as a receiver, when airborne acoustic waves impact it.

This transducer was designed to measure short distances and has a maximum range of 40 cm.

A modified version of Fiorillo's design is used in the Dolphin prototype transmitters and receivers. Sheets of piezo film were procured from Measurement Specialties, Inc.[2] Small transducer elements were cut from the piezo film sheets. As shown in Fig. 2, each element was placed between exposed conductive pads on two pieces of printed circuit board (PCB). Using a screw and bolt adjacent to each of the pads, the two pieces of PCB are held tightly together, rigidly clamping the ends of the piezo film element. The piezo film elements fitted on the transmitter units have a cylindrical length of approximately 5 mm, while those on the receiver units are 10 mm, to allow greater sensitivity.

3.2 Transmitter

Compared to more common ultrasonic transducers, such as piezoceramics, piezo film transducers have low efficiency. For flexibility during experiments, it was desired that the transmitter unit be capable of driving its piezo film transducer with signal levels ranging from tens to hundreds of volts peak-to-peak. As shown in Fig. 3, this was accomplished by using a power op amp with some signal conditioning and a step-up transformer. A Dolphin transmitter unit is shown in Fig. 4, and measures $60\ \mathrm{mm} \times 94\ \mathrm{mm} \times 15\ \mathrm{mm}$. Five of the transmitter units were characterized using measurements taken in an anechoic chamber.

The measured frequency responses of the five units are shown in Fig. 5a. There is little difference in the responses of the individual transmitters. Fig. 5b shows the averaged frequency response for the five units.

The radiation pattern was characterized by measuring the sound pressure level at various angles in two different planes, defined in Fig. 6. The averaged response at 50 kHz of five transmitters for a range of these angles is shown in Fig. 7.

Overall, the characteristics of the Dolphin transmitters are favorable. At one meter, the acoustic output does not vary by more than 10 dB for frequencies from 35 to 100 kHz and for angles of θ and ϕ within 60 degrees.

3.3 Receiver

The relatively low piezoelectric efficiency of piezo films again dictated design decisions for the receiver prototype. An electrometer in a charge amplifier configuration was used to amplify the low-level signal produced by the piezo film element, as shown in Fig. 8. Because of the sensitivity of the electrometer preamplifier stage, it was necessary to electromagnetically shield the receiver circuitry (Fig. 9). Otherwise, radiation from outside sources, such as the high voltages which are possible at the transmitter, can create unacceptable signal-to-noise ratio conditions.

The sensitivity characteristics of five Dolphin receivers were measured in an anechoic chamber. At one meter, the receiver units possessed an average sensitivity of 1,724 mV/Pa at 50 kHz. Fig. 10a shows their responses in

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[2] The polymer film was 28 mm thick, and both sides of the sheets had been electroded with a thin layer of vacuum-deposited copper-nickel metal alloy.

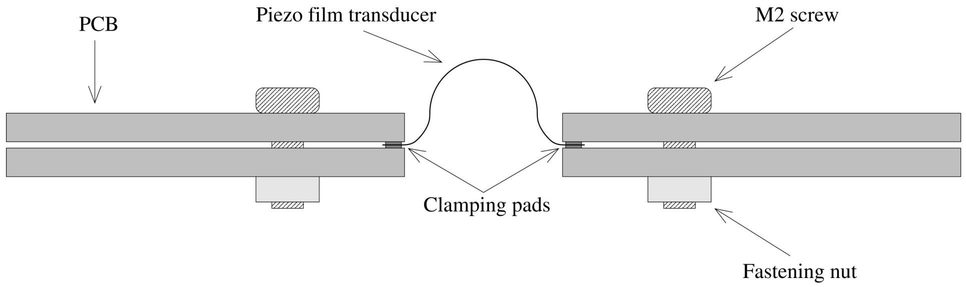


Fig. 2. PCB piezo film mounting. The piezo film element is clamped between conductive pads on two pieces of printed circuit board.

decibels, referenced to this sensitivity, while Fig. 10b shows the averaged frequency response.

Fig. 11 displays the 50 kHz sensitivity within the θ and ϕ planes (defined in Fig. 6), averaged for the five receivers. The plotted sensitivities are expressed in decibels, referenced to the sensitivity at zero degrees.

The behavior of the receivers is not as close to the ideal as that of the transmitters. The frequency response varies by 25 dB across the inspected frequency range. The authors suspect that the receiver frequency characteristic may be adversely affected by the metal mesh shielding, or possibly the electrometer preamplifier circuit, but further characterization of the receiver would be necessary to determine the cause.

With regard to beam pattern, receiver sensitivity is within 10 dB for $|\theta| \leq 60^\circ$ and significant sidelobes are visible at $\theta = \pm 45^\circ$. Note that the ϕ beam pattern is within 10 dB for angles between $\pm 60^\circ$ for the transmitters, but only $\pm 45^\circ$ for the receivers. Longer cylindrical lengths tend to focus the beam pattern more [23]. Since the length of the receiving transducers is twice that of the emitting transducers, this more concentrated beam is expected.

3.4 Channel Bandwidth

The average frequency response of the channel between a Dolphin transmitter and receiver is shown in Fig. 12. For on-axis ranging at a distance of one meter, the channel has 76 kHz of bandwidth above the noise floor. As shown by Table 1, if the signal is attenuated by off-axis transmission or greater distances between the transmitter and receiver, there still remains significant bandwidth above the noise floor.

4 BROADBAND RANGING

With the wide bandwidth characteristic of the Dolphin units, spread spectrum signaling can be employed to achieve a processing gain, allowing ranging to be accomplished at a variety of angles of incidence and room-scale distances. This section discusses a signaling method appropriate for distance measurement with broadband ultrasound and presents the ranging accuracy of the method. A signal processing technique to enhance the multiuser capabilities of the method is then outlined.

4.1 Direct Sequence, Code Division Multiple Access

In a *direct sequence* (DS) spread spectrum system, a data-modulated carrier signal is further modulated by a pseudorandom binary sequence [24]. The rate at which the pseudorandom sequence is applied is usually much faster than the data rate. This has the effect of spreading the spectrum of the signal. One can think of this as distributing the information content (i.e., data) over a large range of frequencies instead of centering it closely about the carrier frequency. Spreading the spectrum in this way makes the signal more robust in the presence of in-band noise. Using DS pseudorandom spreading methods for ranging in a broadband ultrasonic location system would avoid the noise sensitivity limitation of existing narrowband systems.

Gold codes are a particular set of pseudorandom sequences which have desirable auto and cross-correlation properties [25]. If different Gold codes are assigned to users in a spread spectrum system, their signals can be sent simultaneously and still be separated at the receiver. This gives the system multiple-access properties since corruption due to signal collision is minimal. A system which uses

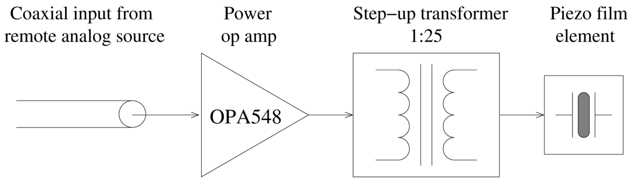


Fig. 3. Transmitter block diagram. An op amp and step-up transformer are used to drive the piezo film element.

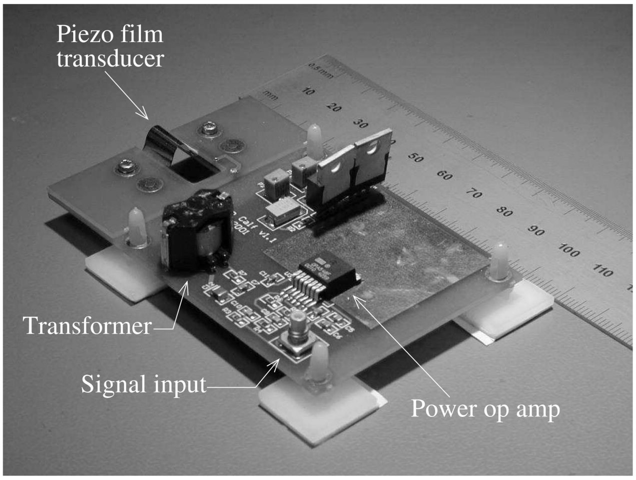
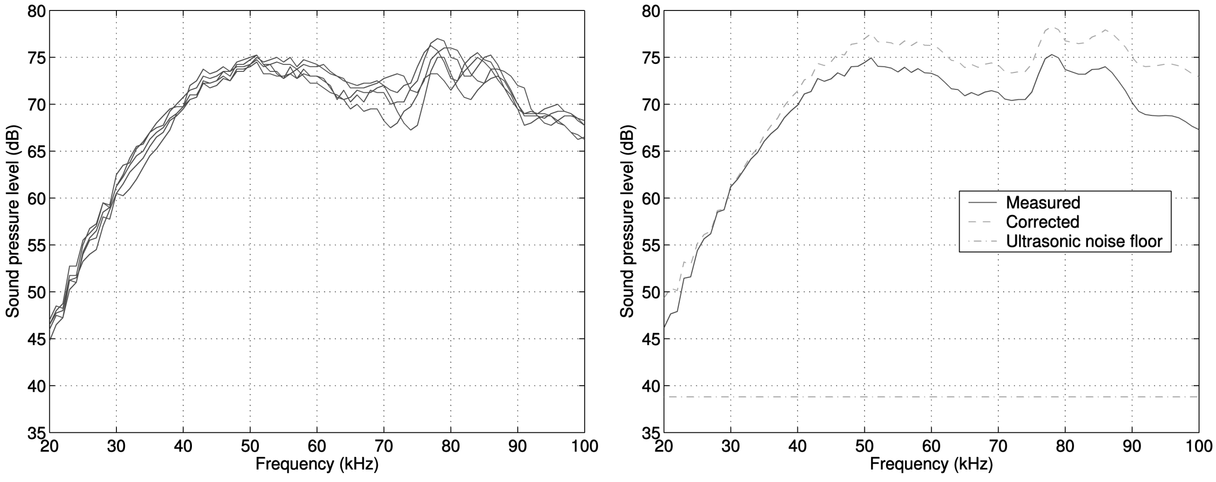


Fig. 4. Dolphin transmitter. In this prototype, power and analog signal generation are provided by external sources.



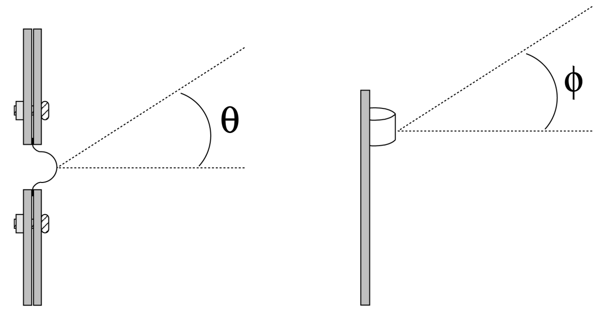
(a) (b)

Fig. 5. Raw transmitter frequency response at one meter. (b) shows a corrected response curve, which has been compensated using the known frequency characteristics of the measuring equipment and the attenuation of ultrasound in air. (a) Individual responses of five transmitters. (b) Averaged response.

codes specially selected to achieve separation of overlapping signals from different users is described as *code division multiple access* (CDMA). Employing CDMA methods for broadband ultrasonic ranging addresses the single-user and identification coding constraints associated with narrowband systems.

DS/CDMA signal structures are appropriate for the Dolphin channel because they make high processing gains to counter low signal-to-noise conditions more easily attainable than other multiple-access methods, such as frequency hopping. The ranging messages used in the experiments presented in this paper consist of a 50 kHz carrier wave, modulated by a Gold code using binary phase-shift keying. The Gold code has a length of 511 bits and is applied at a rate of 20 kHz, yielding a ranging message duration of about 25 ms. Fig. 13 shows the frequency spreading effect when such a Gold code is used to modulate the carrier.

In order to detect the arrival of a ranging pulse, the receiver must *correlate* the received waveform against a version of the signal which is locally generated, using the known signaling parameters. A simple peak detection algorithm can then be used on the correlation result to identify the ranging signal time-of-arrival.



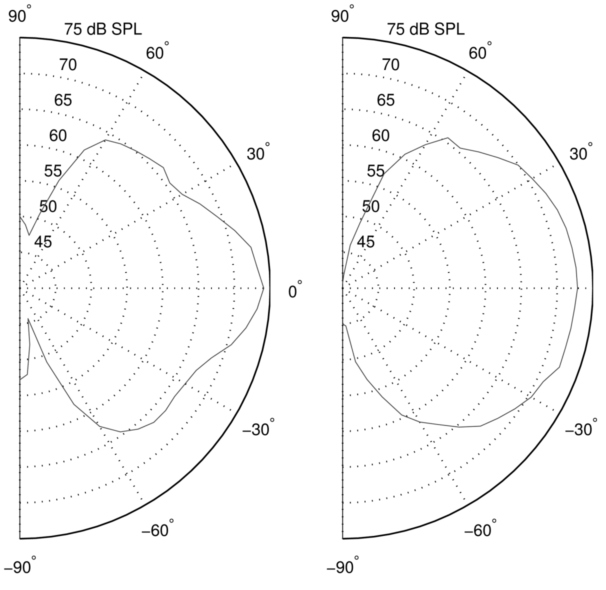
(a) (b)

Fig. 6. Definition of transducer angles of sensitivity. θ describes angles in the plane normal to the transducer's cylindrical axis, while ϕ represents angles in the plane containing the cylindrical axis. (a) Angle described by θ. (b) Angle described by ϕ.

4.2 Ranging Accuracy

DS/CDMA signals have proven to be successful for ranging in previous systems. They are employed in GPS ranging signals [1] and Girod and Estrin have used codes with similar properties in their acoustic ranging system, which operates in the audio frequency range [26].

To verify the ultrasonic ranging accuracy of DS/CDMA spreading using Gold codes, tests were run using a Dolphin



(a) (b)

Fig. 7. Transmitter radiation pattern in two perpendicular planes (see also Fig. 6). (a) θ emission. (b) ϕ emission.

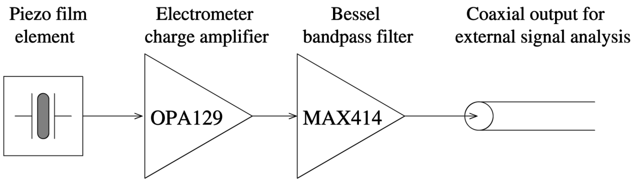


Fig. 8. Receiver unit transducer interface electronics. The electrometer charge amplifier serves as a preamplifier stage, and the bandpass filter removes frequencies outside of the range of interest (20-100 kHz).

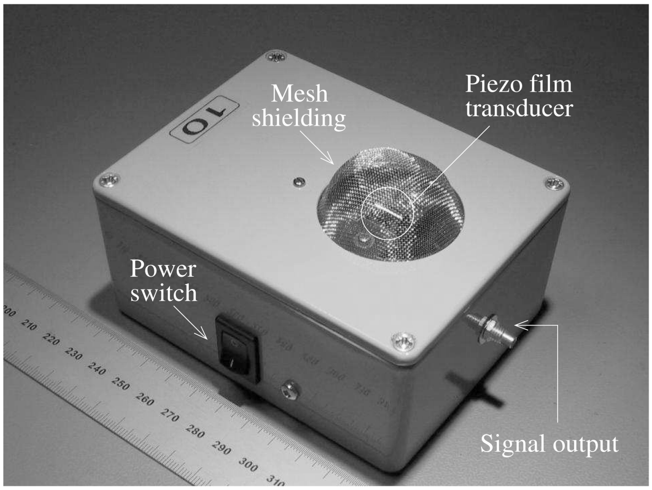
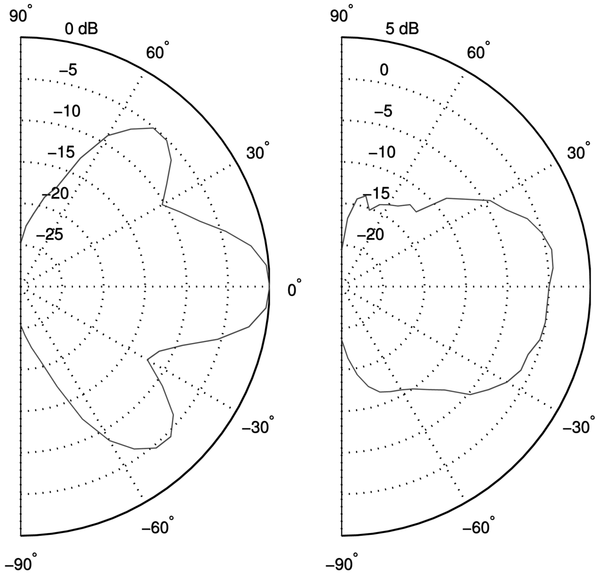


Fig. 9. Dolphin receiver. The housing and metal mesh dome reduce electromagnetic interference. The receiver also contains two standard 9 V batteries which provide power.



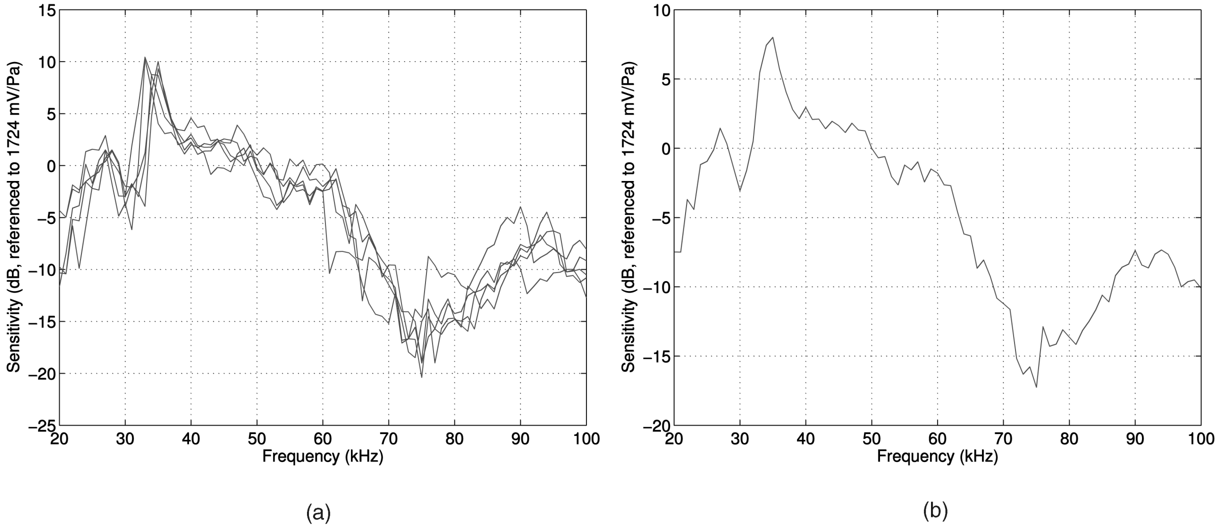
(a) (b)

Fig. 11. Receiver sensitivity pattern in two perpendicular planes (see also Fig. 6). (a) θ sensitivity. (b) ϕ sensitivity.

transmitter and receiver. Signals were generated, captured, and analyzed using a workstation PC with data acquisition and analog output PCI cards. The speed of ultrasound in air (needed to convert a measured time-of-flight to a distance) was estimated with the aid of a temperature sensor. One thousand five hundred ranging measurements were performed at each of five distances between 0.5 and 2.5 m. The ranging error is shown in Fig. 14. Variation of the measurement error with distance is on the order of several millimeters—no more than one might expect from the uncertainty of the hand-measured reference distances used to compute the errors.

4.3 Successive Interference Cancellation

CDMA systems in which many transmitters are sending simultaneously sometimes suffer from the problem of interference between signals, in spite of the fact that the codes chosen might have near-orthogonal properties. This happens when some transmitters have a large signal power at the receiver compared to other transmitters. When trying to demodulate a signal which is many times weaker than other signals present, the cross-correlation peaks due to those other signals can become significant, and the detector



(a) (b)

Fig. 10. Receiver frequency response. (a) Individual sensitivities of five receivers. (b) Averaged sensitivity.

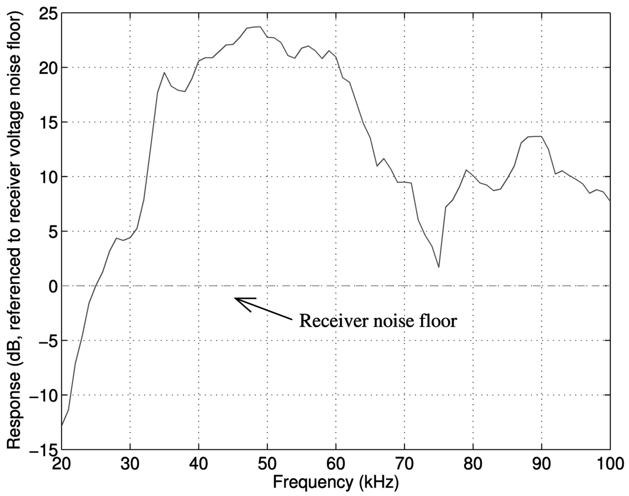


Fig. 12. Average ultrasonic channel bandwidth. Measurements were taken at a distance of one meter, with the transmitting and receiving transducers directly incident.

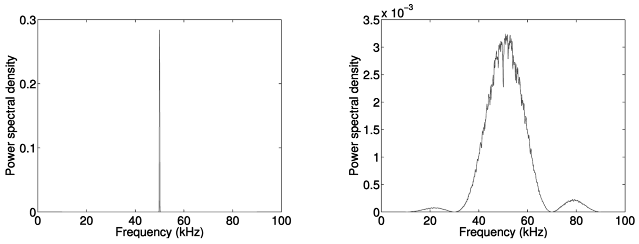
TABLE 1
Effect of Signal Attenuation on Above-Noise Bandwidth

Signal attenuation (dB)	Equivalent on-axis distance (m)	Bandwidth above noise floor (kHz)
0	1.00	76
5	1.78	67
10	3.16	47
15	5.62	30

may be unable to resolve the weak signal. The situation in which one transmitter with a comparatively large signal power causes a degradation in system performance is described as the *near-far* effect.

One way of dealing with multiuser interference in CDMA systems is to employ *successive interference cancellation* (SIC), proposed by Viterbi [24]. A receiver performing SIC first attempts to detect all of the transmitters from which it might expect to see a signal. Once this is done, one transmitter is chosen (which presumably has a large signal power relative to the others), and that transmitter's signal is reconstructed at the receiver and subtracted from the received waveform. The process is repeated until there is only one user remaining.

The difficulty in performing SIC lies in accurately estimating the amplitude of the signal to be canceled. In radio communications, signal amplitude determination is aided by explicit knowledge of the relative user powers, through the use of transmitter power control [27]. However, in an indoor ultrasonic location system with mobile users and devices, the transmitter signal power at the receiver is dependent on the transmitter's location and orientation and is not directly known. Alternative methods allow the signal amplitude to be estimated from the correlation [28]. A similar strategy can be used for SIC processing of broadband ultrasonic ranging signals and is applied in one of the location systems described in the next section.



(a) (b)

Fig. 13. Spreading the spectrum of the ranging message. (a) 50 kHz carrier only. (b) 50 kHz carrier spread by 20 kHz Gold code.

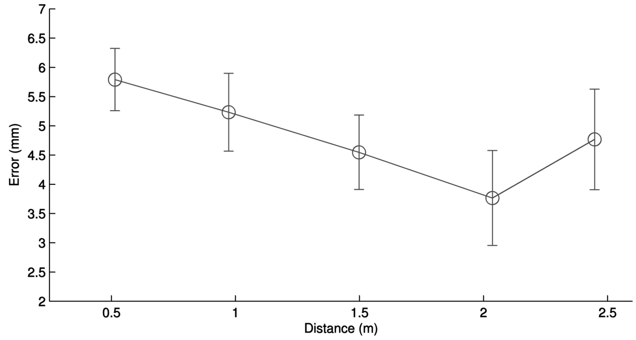


Fig. 14. Transmitter-to-receiver ranging error. The error bars indicate the standard deviation of the measurements at each distance.

5 TWO BROADBAND ULTRASONIC LOCATION SYSTEMS

This section reviews two prototype broadband ultrasonic location systems which employ Dolphin units. The systems have fundamentally different architectures and, taken together, illustrate the advantages provided by broadband ultrasound. Comments are then given on the hardware modifications needed to make the Dolphin prototypes appropriate for wide-area deployments and use by mobile users.

5.1 Polled, Centralized Location System

Some ultrasonic location systems are *polled*, meaning that transmitters are told when to send their ranging messages, whereas others are *centralized*, indicating that there is a central service which collects the time-of-flight data and uses it to estimate the locations of mobile tags. The Bat is an example of a polled, centralized location system. Since the transmitters are centrally coordinated, such systems tend to have superior update rates compared to other architectures.

The Dolphin prototypes were used to implement a polled, centralized location in a small office [29]. Eight receivers were affixed to the ceiling, and their positions accurately surveyed. Four transmitters were placed at fixed positions in the room, about 0.75 m above the floor. An additional transmitter, the *mobile unit*, was placed at 64 test locations within the small office. The test points covered a variety of heights (10 to 140 cm above the floor) and included locations in close proximity to walls and hard furnishings, which tend to cause ultrasonic reflections. A temperature sensor was placed in the room, in order to allow accurate estimation of the speed of sound in the air. As with the distance accuracy measurements presented above, all signal generation, capture, and analysis was performed on a workstation PC.

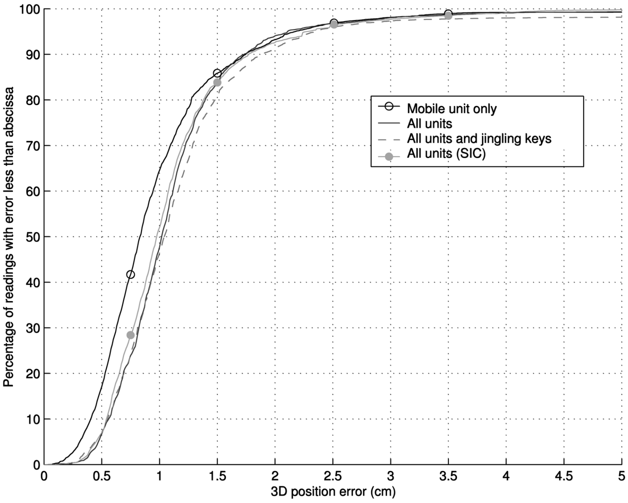


Fig. 15. Accuracy of location estimates in the polled, centralized system.

5.1.1 Location Estimation

The location of the mobile unit was estimated using the following steps:

1. The times-of-flight of the mobile unit's ranging messages were measured by correlating the receivers' signals against the expected signal (a 50 kHz carrier modulated by the mobile unit's Gold code). The time-of-flight was defined as the time between the triggering of the transmitter and the occurrence of a large peak in the correlated data.
2. The times-of-flight were converted to transmitter-to-receiver distances using the speed of sound in air.
3. Using the accurately surveyed positions of the receivers and the transmitter-to-receiver distances, location was estimated by employing the multilateration algorithm described by Ward et al. [30].

Since the receivers are coplanar, a minimum of three distances is needed to estimate the mobile unit's position, with the assumption that it is below the ceiling. However, it was required that at least four distances be measured, enabling the multilateration algorithm to estimate the errors of its produced locations. The algorithm does not return a position estimate if there are fewer than four transmitter-to-receiver distances or if the distances have a high error estimate.

5.1.2 Results

Five hundred location readings were taken at each of the 64 test points for four test cases:

1. the mobile unit transmitting by itself,
2. the mobile unit and the four fixed units transmitting simultaneously,
3. the mobile unit and the four fixed units transmitting simultaneously in the presence of noise (i.e., jingling keys),[3] and
4. the mobile unit and the four fixed units transmitting simultaneously, with SIC processing applied.

TABLE 2
Polled, Centralized Location System Performance

Test case	Readings returned (%)	95% confidence level (cm)
Mobile unit only	93	2.2
All units	75	2.1
All units and jingling keys	68	2.3
All units (SIC)	85	2.3

Fig. 15 shows the error distribution functions of the *returned* locations for the mobile unit in the four test cases. Table 2 indicates the percentage of readings for which the algorithm returned a location estimate. The 95 percent confidence levels of the 3D position accuracies are also listed.

5.1.3 Advantages

The results clearly show that the broadband system *performs robustly in the presence of noise* which would have caused typical narrowband ultrasonic location systems to fail to return location estimates. Although the location algorithm returned fewer readings in the presence of noise, the accuracy of the location updates was not significantly affected.

It is also demonstrated that the system has a capacity for *increased aggregate update rates* since multiple transmitters can emit ranging their signals simultaneously and be successfully detected at the receivers. With the signaling parameters chosen, the maximum update rate for a single transmitter is about 40 Hz. However, given the Gold code length, up to 513 transmitters could simultaneously emit near-orthogonal ranging signals, yielding a maximum theoretical aggregate update rate of about 20 kHz. Although, in current scenarios, it is doubtful that this upper limit is easily achievable or even necessary, it does demonstrate that broadband systems can produce location updates many times faster than narrowband solutions. In the above results, the multiuser test case produces about 20 percent fewer location readings than the single user case, but this can be alleviated by employing SIC processing.

The last important conclusion is that the system can produce *near-simultaneous location updates for different transmitters*. Because of the multiple-access nature of the system, latency between the location updates for different transmitters is minimal. Thus, such a system would have superior performance for applications which require near-simultaneous updates for different objects. Examples include 3D mice, gesture recognition, augmented and virtual reality, and the simultaneous tracking of moving people and the devices they carry.

5.2 Privacy-Oriented Location System

Some research has been directed toward more *privacy-oriented* solutions to location sensing.[4] Ultrasonic location systems

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[3] This type of noise has been known to make narrowband ultrasonic location systems fail to report location estimates altogether.

[4] It remains to be seen whether such systems provide benefits for the user in practice—denying location information to external devices severely limits the applications which can be made available, and complications arise when trying to reliably authenticate and distribute location information without being compromised by an attacker.

which are meant to allow complete security and control for the privacy-conscious user should have two properties: 1) a user's presence is not advertised, even anonymously, and 2) entities outside of the user's control are not entrusted with gathering signal times-of-arrival or with calculating the user's location; otherwise, these entities may relay that data to other parties without permission.

In order to have the first property, the location system should be designed such that mobile units do not need to emit any sort of detectable signal. By detecting emission of a signal, an observer might be able to infer the number of users present in an area. To have the second property, a mobile unit must use its own sensors to detect ranging signals broadcast from places in the environment, thus avoiding reliance on external sensing devices. Additionally, the mobile unit must have knowledge of the surveyed locations of the environmental transmitters, so that it may calculate its position autonomously using the times-of-arrival it gathers. Cricket is an example of a privacy-oriented location system.

Dolphin prototypes were deployed as a privacy-oriented system [31], with seven ceiling transmitters which broadcast simultaneously using the DS/CDMA signal structure described above. A mobile receiver was placed at the same 64 test locations used in the polled, centralized system experiments. As before, the speed of sound in air was estimated with the aid of a temperature sensor and a workstation PC performed the signal processing.

5.2.1 Location Estimation

The narrowband ultrasonic location systems reviewed above and the polled, centralized system just presented utilize synchronized transmitters and receivers. In *synchronous* ultrasonic location systems, receivers have knowledge of when ranging signals depart from transmitters. Thus, they can directly measure the signal times-of-flight and convert them to transmitter-to-receiver distances using the speed of sound in air. Location is then computed using a multilateration algorithm.

With the privacy-oriented system described in this paper, the case of receivers operating asynchronously can also be considered. *Asynchronous* receivers do not have explicit knowledge of when ranging signals depart from transmitters. Rather, they only know when transmitters send their signals with respect to one another. With this knowledge, it is possible for a receiver to gather a number of times-of-arrival and calculate its position, despite the fact that it cannot measure signal times-of-flight directly.

Since the transmitter-to-receiver distances are unknown, conventional multilateration cannot be applied. However, a receiver can pick an arbitrary point in time from which to reference its signal time-of-flight measurements. Assuming knowledge of the times when transmitters broadcast relative to one another, the receiver can create a set of *pseudoranges*. The pseudoranges are not the actual transmitter-to-receiver ranges; instead, the gathered pseudoranges have an equal offset from the true transmitter-to-receiver distances. The distance offset is directly related to the difference between the time at which the transmitters began sending their ranging signals and the time arbitrarily chosen by the receiver to begin taking data. GPS receivers utilize pseudoranging since a receiver's clock is not necessarily synchronized with the system-wide clock.

To arrive at a location estimate, four pseudoranges are required since the unknown distance offset must be estimated in addition to the receiver's 3D coordinates. If a measure of the standard error is desired, five or more pseudoranges are needed. Details of a regression-based location algorithm which employs pseudoranges have been previously described [31].

Compared to receivers in synchronous systems, asynchronous receivers have the disadvantage that they must gather one more signal time-of-arrival in order to compute a location. Also, their location estimates tend not to be as accurate since the algorithm must fit four parameters to the data instead of three. However, the advantage of asynchronous receivers is that they do not need the capability to receive a wireless synchronization signal.

As with the polled, centralized system, it was required that the standard error be estimated, so that sets of incongruous readings can be rejected by the algorithm. Thus, in the results presented below, at least four transmitter signals must be detected for each location reading in the synchronous system and five for the asynchronous system. The algorithm does not return a position estimate if there are too few signals detected, or if the location solution has a high error estimate.

5.2.2 Results

Five hundred location measurements were taken at each of the 64 test points to assess system performance, for both synchronous and asynchronous receiver operation. Fig. 16 shows the accuracy distribution of the readings, and Table 3 reports the 95 percent confidence levels of the 3D position estimates (and their horizontal component), as well as the fraction of readings returned by the algorithms.

The 3D accuracy of a synchronous receiver is better than 5 cm in 95 percent of cases, a level competitive with that of the systems previously discussed. The 95 percent 3D accuracy of an asynchronous receiver is much worse—over 25 cm. This is because the nearly coplanar placement of ceiling transmitters creates an interdependency between two of the quantities estimated by the location algorithm—the distance offset of the pseudoranges and the vertical component of position. As Table 3 indicates, the vertical error component contributes far more to the asynchronous receiver's 3D position error than the horizontal error component. However, many location-aware applications require only that the horizontal positions of people and objects be fine-grained; the vertical component tends to be less significant. Although the asynchronous receiver's 3D accuracy is much worse than that provided by some existing systems with synchronized receivers, it can still provide location data with a horizontal 95 percent accuracy of less than ten centimeters.

The number of readings returned by the asynchronous receiver was about 20 percent lower than those returned by the synchronous receiver. This is because the asynchronous receiver needs to detect at least five signal times-of-arrival to calculate its location and an error estimate, whereas the synchronous receiver only requires four. Thus,

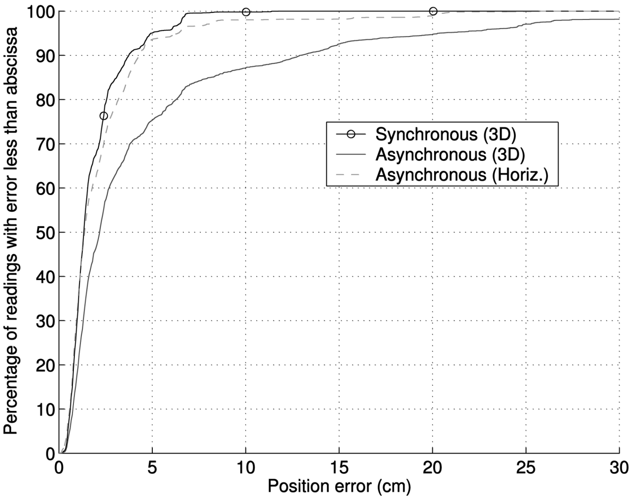

Fig. 16. Accuracy of location estimates in the privacy-oriented system.

the asynchronous receiver had to identify five of the seven available transmitter signals.

Also, at heights close to the ceiling, many synchronous and asynchronous receiver readings failed to return enough times-of-arrival to perform multilateration. Characterized previously [31], this effect occurred because of the radiation pattern of the Dolphin transmitters and their particular arrangement on the ceiling. The proportion of readings returned for both types of receiver operation can be much improved by adding a few more transmitters to the system, or slightly modifying their ceiling placement scheme, as proposed elsewhere [31].

5.2.3 Advantages

Since a receiver can successfully detect the multiple, simultaneously sent ranging signals, the broadband system allows *superior per-receiver update rates*. With the signal structure chosen, the location update rate of each mobile unit performing back-to-back correlation operations would be 40 Hz for both the synchronous and asynchronous cases. This is superior to previous narrowband privacy-oriented systems (Section 2.1).

Similarly, the DS/CDMA simultaneous ranging signals enable *increased dynamic tracking performance*. Receivers in privacy-oriented systems employing narrowband ultrasound must measure times-of-arrival from transmitters individually, one at a time. For users and devices which are in motion during the measurement process, this means that the collected signal times-of-arrival may not correspond well, resulting in a loss of location accuracy. It is possible to partially alleviate this by including the receiver velocity as a parameter in the location model, using single-constraint-at-a-time tracking [7]. However, removing the single transmitter constraint altogether with a broadband solution would only improve the performance of such techniques.

Last, the experiments show that location systems using broadband ultrasound can have *enhanced identification encoding*. Assuming transmitters are assigned unique spreading codes, their signals can be identified by the receiver. This removes the need to identify them using some other means of communication, which can be beneficial for systems where many transmitters are sending simultaneously at high rates. Also, as shown by the experiments with the asynchronous receiver, individually identifiable signals are also crucial for systems in which there is no dedicated communications channel.

TABLE 3
Privacy-Oriented System Performance

Test case	Readings returned	95% confidence level (cm)	
		3D	Horizontal
Synchronous	67	4.9	4.9
Asynchronous	48	26.6	8.5

5.3 Modifications Needed for Production Systems

As mentioned above, the Dolphin units were designed to be flexible, for application in experimental location systems. In order to realize wide-area location system deployments for everyday use by many people, a number of changes would need to be made.

Both the transmitter and the receiver are too large and bulky to be used as mobile tags or unobtrusively installed in the environment. Before being deployed for everyday use, the devices would be reengineered, and parts chosen which are more appropriate for small, unobtrusive devices. For units intended to be mobile, components could be chosen which have sufficiently low operating voltages so that they could be powered by a single-cell battery.

In the experiments presented in this paper, Fast Fourier Transform (FFT) operations running in software on the workstation PC were used to correlate the received signals with the expected spread spectrum waveforms. Since FFTs are computationally expensive, specialized hardware correlators would most likely be employed in a deployable version of the Dolphin receiver unit. Miniaturization of an integrated receiver unit is certainly feasible—GPS receivers, which perform essentially the same operations at much higher speeds, have been successfully engineered to fit into PCMCIA cards.

6 CONCLUSION

This paper has reported on the exploration of broadband ultrasonic location systems. Because broadband systems can utilize spread spectrum, multiple access techniques in their ranging signals, they have the potential for significantly higher performance in a number of aspects of system operation than narrowband ultrasonic location systems.

The Dolphin transmitter and receiver prototype hardware was described and characterized in detail. Small, inexpensive piezopolymer transducer elements were employed in the units using a compact mounting method. The sensitivity characteristics of the receiver and transmitter provide acceptable signal levels up to 45 degrees and 60 degrees off-axis, respectively. The bandwidth of the resulting ultrasonic channel was shown to be much greater than narrowband transducers allow, even at room-scale distances and for transmitter and receiver units not directly facing one another.

An appropriate DS/CDMA ranging message signal structure was then outlined and its ranging accuracy with the Dolphin prototypes shown to be about half a centimeter. The Dolphin units were used to create two broadband ultrasonic location systems. A polled, centralized system with ceiling receivers and roaming transmitters was shown to have 2 cm accuracy. A high fraction of the readings taken yielded a successful location result, especially with the application of successive interference cancellation. A privacy-oriented system with ceiling transmitters and roaming receivers had slightly less accuracy and fewer successful readings, due primarily to differences in ceiling unit deployment. Despite this, the privacy-oriented system performance is appropriate for many fine-grained, mobile computing applications.

Most importantly, both systems have a number of advantages over their narrowband counterparts. The performance enhancements for location systems using broadband ultrasound can be summarized as follows:

1. **Noise robustness.** Ranging signals can be resolved in the presence of in-band noise, allowing the system to continue to return location updates even when sensors are colocated with aggressive noise sources.
2. **Increased update rates.** Simultaneous multiple access signals allow many transmitters to be detected, without the restriction that transmitters emit ranging signals one-at-a-time. This manifests vastly increased aggregate update rates for polled, centralized systems, and much improved per-receiver update rates for privacy-oriented architectures.
3. **Low-latency positioning.** Simultaneous multiple access signaling can also provide negligible latency between ranging measurements to different transmitters. In polled, centralized systems, this means location updates for multiple people and devices can be nearly simultaneous. In privacy-oriented systems, this much improves the dynamic tracking capacity for mobile users.
4. **Enhanced identification encoding.** Since broadband signals have a much greater capacity to carry information, transmitter signals can be uniquely identified at the receiver. This can reduce the load on other wireless communication channels available (such as radio or infrared) and, in some cases, avoid reliance on external channels altogether.

For a more detailed look at the concepts, devices, and systems presented in this paper, the reader is referred elsewhere [32].

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