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Live event performer tracking for digital console automation using industry-standard wireless microphone systems

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ABSTRACT

The ever-increasing popularity of digital consoles for audio and lighting at live events provides a greatly expanded set of possibilities regarding automation. This research works towards a solution for performer tracking using wireless microphone signals that operates within the existing infrastructure at professional events. Principles of navigation technology such as received signal strength (RSS), time difference of arrival (TDOA), angle of arrival (AOA) and frequency difference of arrival (FDOA) are investigated to determine their suitability and practicality for use in such applications. Analysis of potential systems indicates that performer tracking is feasible over the width and depth of a stage using only two antennas with a suitable configuration, but limitations of current technology restrict the practicality of such a system.

1. INTRODUCTION

The steady progression of digital technology in the live event industry has opened the door to a wide-range of new technological possibilities. Many of these advances focus on ease-of-use, often in the form of tablet-based console control or various convenient functions such as scene automation and musician-controllable monitor mixes. While most of these functions are extremely useful, they still require the engineer to make adjustments in real-time due to the typically unpredictable and unscripted nature of many live events.

Considering the ever-expanding capabilities of digital mixing consoles, it must be asked what else can be done to ensure industry professionals take full advantage of the available technology? While this research doesn't present a final product ready for immediate use in the field, it details one possible application with the hope that it may eventually be developed into a robust algorithm put to use in the live event industry.

The primary area in question here is stereo panning. There are often numerous performers moving about a stage at any given moment. In theatrical productions, there are actors continuously roaming around the stage while at musical events it is increasingly uncommon to have musicians at fixed positions for the duration of a show. These performers are likely to have wireless microphones which transmit their voices (or instrument signals) via radio frequencies to receivers offstage.

This work proposes that transmitted signals can be used for a secondary purpose: to track the performers on (and potentially off) stage. This would allow for automated stereo panning on digital audio consoles and follow-spot automation on lighting consoles (among other things). This research explores how to achieve this, relying heavily on navigation theory.

The paper begins with an overview of existing radio frequency-based localization methods, most of which are drawn from the navigation industry (section 2). The discussion moves to live event performer tracking capabilities and to what extent these are used in industry (section 3). Section 4 steps through a variety of wireless microphone system configurations, exploring potential tracking methods and the resulting accuracy of each. This is followed by a practical discussion on the feasibility of such proposed systems in real-world scenarios (section 5) and the paper is concluded in section 6 with a number of proposals for future work in this area.

2. EXISTING RADIO FREQUENCY-BASED LOCALIZATION METHODS

With the steady increase in popularity of smart phones, navigation has become available to the general public where in the past it has largely been limited to military and commercial transportation applications. The majority of navigation/tracking technology relies on the global positioning system (GPS), which comprises of a set of satellites orbiting the Earth, allowing for individual users to triangulate their position based on timing information in the signals [1].

A major drawback to GPS is that users must have a direct line-of-sight to the satellites for the system to operate properly [1]. This has led to a wealth of research concerning indoor navigation. Numerous methodologies have been developed and put into practice for this purpose, which are discussed in detail in this section, highlighting the advantages and disadvantages of each. Particular focus is placed on the viability of each method in terms of applications with wireless microphone signals at live events.

2.1. Received signal strength (RSS)

Perhaps the most straightforward non-GPS tracking technique is the use of received signal strength (RSS). The underlying principle is the nature of signal propagation through air. Assuming a radio frequency (RF) transmitter sends signals in an omnidirectional manner, the same inverse square propagation law that is familiar in acoustics can be applied (Eq. 2.1) [2]:

$$P(r) = P(r_o) - 10\log_{10}\left(\frac{r}{r_o}\right) \tag{2.1}$$

where $P(r)$ is the received power (dB) with the receiver at distance, r (m), and $P(r_o)$ is the reference power (dB) when the receiver is at a known position, r_o (m). As in acoustics, for every doubling of distance, the received power is reduced by a factor of 4, corresponding to a 3 dB loss in power. This formula doesn't take into account any environmental attenuation of signal strength. Since this work deals with RF signals over (relatively) short distances this can be ignored, but if environmental attenuation is a contributing factor, a loss exponent, n, can be inserted as a multiplier of 10 in front of the logarithmic term in Eq. 2.1 [2].

In a free-field RSS is extremely reliable in judging distance due to the direct proportionality of the received power level to distance. Unfortunately, a free-field is rare in practice and received signals are routinely corrupted by reflections which can limit confidence in RSS-based systems [3]. In a live event setting, it is common to have large metallic objects surrounding (and on) a stage which can produce strong reflections of the RF signal(s), potentially causing significant issues.

RSS localization requires a calibration step (or at least the knowledge of the transmission power). While this isn't likely to be a major inconvenience, if anything is altered during a show, recalibration may be required. The issue of calibration is addressed in section 5.

2.2. Angle of arrival (AOA)

There are various approaches to localization based on a signal's angle of arrival (AOA). The simplest technique, which may be the most suitable AOA method for live event applications, is using a single-output directional antenna [2]. Like RSS-based localization, this approach monitors strength of the received signal. Instead of relating signal strength to distance, the signal strength is related to the angle off-axis from the antenna.

When a signal arrives perfectly on-axis, the received strength is maximal (ignoring any signal degradation due to reflections). As the transmitter moves further off-axis, though, signal strength decreases, giving indication of the angular location of said transmitter [2].

This simplistic form of AOA localization doesn't provide a complete set of positioning information. There is nothing to deduce transmitter distance or what direction off-axis the source has moved.

A more detailed and robust approach to AOA localization utilizes a multicomponent, multiple-output antenna. The antenna array adjusts internal phase relationships between components to steer its overall polar pattern so that the received signal is maximized [2]. When the signal is at a maximum, the antenna directivity is oriented in the direction of the source. The critical aspect in such a system is antenna component spacing. The spacing defines the frequency range over which the device is accurate, therefore such a design can only be put to use over a narrow frequency band [2].

As with the simplistic approach to AOA, this method doesn't necessarily define the propagation distance of the transmitted signal. Additionally, a multiple-component antenna isn't viable when limited to industry-standard wireless microphone technology; therefore, this AOA approach isn't practical for the purposes of this work.

2.3. Time difference of arrival (TDOA)

Unlike the single antenna localization approach of RSS and AOA methods, time difference of arrival (TDOA) utilizes two or more spatially separated receivers [4]. This is directed by the fact that the transmitter signal has different propagation path lengths to each receiver. This difference leads to different propagation times. As long as the transmitter isn't equidistant from all receivers, there will be a time difference of arrival within the receiving system. The TDOA between two antennas is calculated based on the propagation distances, r_1 and r_2 (m), and the speed of propagation, c (m/s) (Eq. 2.2) [4].

$$\tau = (r_2 - r_1)/c \tag{2.2}$$

In practice, the exact propagation distances are unknown. Some signal analysis is needed to determine TDOA from a limited set of information. A common approach is to calculate the cross-correlation of two received signals [4]. The time offset of the maximum value of the cross-correlation vector indicates time delay between arrivals. The cross-correlation of continuous-time and discrete-time signals, x and y, are given by Eq. 2.3 and 2.4, respectively [5].

$$\phi_{xy}(t) = \int_{-\infty}^{\infty} x(t+\tau)y(\tau)d\tau \tag{2.3}$$

$$r_{xy}(l) = \sum_{n=-\infty}^{\infty} x(n-l)y(n) \tag{2.4}$$

The TDOA between two receivers defines the transmitter location as lying on the surface of a defined hyperboloid [4]. The more receivers in the system, the more intersecting hyperboloids there will be, allowing an increasingly precise transmitter location prediction. Typically, a transmitter's planar (2D) location can be judged using TDOA with two receivers and spatial (3D) location with three receivers [4].

As with RSS and AOA, TDOA is prone to degradation due to strong reflections, but this can be avoided with appropriate time windowing of incoming signals as well as careful implementation of the cross-correlation function [6]. Additionally, TDOA requires hardware capable of sampling a signal at very high frequencies (GHz range required for wireless microphones). This requirement may not be practical for the variety of applications discussed in this paper. This will be considered in sections 5 and 6.

2.4. Frequency difference of arrival (FDOA)

A slightly different localization method to TDOA is frequency difference of arrival (FDOA). FDOA has been used in astronomy for many years (commonly referred to as very long baseline interferometer – VLBI), but has also been applied to terrestrial navigation since the late 1970s [4, 7]. The technique is based on difference in received frequency at two receivers. If the tracked source is in motion, the signals are prone to the Doppler Effect. The Doppler Effect occurs due to compression/expansion of the electromagnetic waves as a transmitter (or receiver) moves relative to the other (Eq. 2.5) [8].

$$f_{Rx} = f_{Tx}\frac{c - v_{Rx}}{c - v_{Tx}} \tag{2.5}$$

where f_{Rx} and f_{Tx} are the receiver and transmitter frequencies (Hz), respectively, c is the propagation speed in the medium (m/s) and the receiver and transmitter velocities (m/s) are given by v_{Rx} and v_{Tx}, respectively. When measured over a finite period of time, the average received frequency is calculated using Eq. 2.6 [4].

$$f_{avg} = f_c - (r_2 - r_1)/\lambda T \tag{2.6}$$

where f_{avg} is the average received frequency (Hz) over time, T (s), f_c is the carrier frequency at the transmitter (Hz), r_1 and r_2 are the starting and final positions, respectively, in meters and λ is the carrier frequency wavelength (m). If the received and transmitted frequencies are known, then the change in distance over the time period can be directly calculated.

For this method to work in navigation, a second receiver is needed. The average frequency is monitored at both receivers and the difference between the two resulting values gives an FDOA reading [4]. This means that the system works without knowledge of the transmitted frequency since it's the difference in received frequencies that is important. FDOA is calculated using Eq. 2.7 and, as with TDOA, results in a three-dimensional surface where the transmitter must lie [4].

$$f_d = f_1 - f_2 = (1/\lambda T)[r_{22} - r_{21} - r_{12} + r_{11}] \tag{2.7}$$

where the first and second number in the subscripts represent the receiver number and transmission location, respectively. If another FDOA measurement is taken (with an additional receiver) the two surfaces give an intersection and a definite location of the transmitter [4].

The advantage of FDOA is that it isn't prone to reflection-related degradation. A distinct disadvantage to this procedure, however, is that if the transmitter is stationary (as is the case at points in most performances) then all FDOA measurements will be zero, making tracking impossible. This is why it is common for non-GPS navigation to employ a combination of FDOA and TDOA for instantaneous localization [4].

In addition to this issue, performers at live events are only going to move at a few meters per second at any point in time. Compared to the propagation speed of RF signals (the speed of light), the tracking system would have to have significantly high resolution to detect any change in received frequency. This makes FDOA currently impractical for the purposes of this work.

3. EXISTING LIVE EVENT PERFORMER TRACKING TECHNOLOGY

Welch and Foxlin [10] describe a wide range of available tracking technologies. Of these there are two main approaches applied to performer tracking. Video systems can be used to track a performer with markers or image processing systems. Alternatively, a performer wears a device that interacts with radio or audio signals to provide localization within a defined space.

Video tracking systems often utilize infrared (IR) markers which are not apparent to the naked eye. Either the performance area is lit with IR light and the marker is a passive reflector or the marker may be emissive such as an IR light emitting diode (LED). Often the camera is overhead so the stage width and depth coordinates can be determined, but height data is harder to calculate without additional cameras and markers. Care must be taken that the camera's view of the marker is not occluded and these systems have difficulties discriminating between individual performers [11].

Video-based tracking systems can be implemented without markers. Difference tracking compares the current video frame with a reference image of the unoccupied performance space. The location of any altered pixels is used as tracking data. Changes in the environment that are not related to performer movement (e.g. change in ambient light levels, introduction of a new piece of fixed scenery, etc.) will produce false-positives unless a new reference image is acquired. Threshold tracking utilizes IR light to give the camera a high contrast image where either the performer or the background is highly reflective to the IR source [12]. Environmental changes need not adversely affect the tracking but it is still difficult to differentiate between individuals and multiple cameras would generally be needed for accurate localization in three dimensions.

Sophisticated image processing algorithms allow performer tracking based on real-time analysis of a scene without the need for IR light sources. With sufficient resolution, individual performers could be tracked through face recognition methods and skeleton-tracking (whereby the coordinates of individual body parts can be determined).

The use of stereoscopic cameras or systems that utilize structured light can improve the fidelity of three-dimensional localization by adding explicit depth information to the scene description. The Microsoft

Kinect (a controller peripheral for the Xbox360 games console) projects a known pattern of IR dots over the scene. A camera detects the dots and the original “flat” pattern is compared with the received image, which will be “distorted” by the topography of the scene to produce an accurate depth map. This image can be used for difference tracking or further processed in combination with the image from the visible light camera to provide skeleton tracking data [13]. A number of attempts have been made to use the Kinect for performer tracking, however the range of the device is limited (approximately 7 meters) and problems can still occur with environmental changes (such as lighting), occlusion and misinterpretation of skeleton data.

Many of the limitations of video tracking can be overcome by utilizing radio frequency or ultrasonic tracking methods. Both the Wybron Autopilot [14] and the Martin Lighting Director [15] (both out of production) uses ultrasonic signals to track performers. The Autopilot system has each performer wear a beltpack that emits an ultrasonic signal. These signals are detected by a number of receivers (typically 8) that are in fixed, known locations around the performance space. Conversely, the Lighting Director system utilizes four, fixed ultrasonic emitters with each performer wearing a modified radio microphone that transmits the received signal to the control unit. In both systems the location of performers is determined using time difference of arrival (TDOA).

The TiMax Tracker from Outboard “…uses Ultra Wideband (UWB) radar technology” to track the performers in three dimensions [16]. Each performer wears a small UWB pulse transmitter tag operating in the 6-8 GHz band. A number of sensors around the performance space receive the signals and localization is achieved with a combination of angle of arrival (AOA) and TDOA. The TiMax system has been used extensively in live music events and is particularly well known for its utilization in large scale opera productions. A similar product, Stagetracker, is available from Total Theatre Audio [17].

CAST Software’s BlackTrax is aimed at all applications of performer tracking, not specifically vocal localization [18]. The BTBeacon worn by the performer contains an RF transmitter, IR LED, gyroscope and accelerometer. This produces data with six degrees of freedom (x, y and z coordinates plus pitch, roll and yaw) such that a performer’s orientation as well as location can be determined. The orientation data is transmitted by RF whilst location tracking is carried out by overhead cameras that track the IR LED. If the LED becomes occluded, the on-board inertial measurement unit will continue to transmit location data via the RF link. Despite having been released in late-2011, there seems to be few examples of its use. However, it was recently announced that BlackTrax will be a technical partner of the Eurovision Song Contest, where the system will be used during the live broadcasts in May 2013 [19].

4. WIRELESS MICROPHONE TRACKING

A highly-complicated RF-based wireless microphone tracking system can be developed based on the techniques presented in the previous section, however this isn’t the aim of this research. An entirely new system (with impressive accuracy) is likely to require investment in new technology for use at live events. A more realistic approach would allow tracking (and resulting automation) to be built into the processing of existing industry-standard devices. This would limit the uptake costs within industry and promote use as companies wouldn’t have to replace their existing stock.

The question, therefore, is what is the simplest implementation of such a system that provides accurate tracking of multiple performers? This section explores the performance of various systems to highlight what can reasonably be achieved in practice without requiring any additional equipment.

4.1. One antenna

The simplest wireless microphone system utilizes a single antenna. This approach isn’t ideal for a number of reasons, without even considering tracking purposes. A single antenna prohibits antenna diversity raising the issue of dead-spots on stage due to direct and reflected signals being 180° out of phase, causing cancellation. A dual-antenna approach circumvents this issue by taking the stronger of the two antenna signals or cleverly mixing the two signals to ensure only constructive interference occurs [9].

Although a single antenna approach isn’t ideal (and not likely acceptable to professional live sound engineers) its localization capabilities are considered here for completeness. When dealing with a single antenna, the localization system is limited to received signal strength (RSS) since no other antenna signal is available for comparison. Once the antenna is placed (most likely off stage left/right in “monitor world”) a calibration measurement is necessary where the transmitter position must be known and fed into the system. Once calibration is complete, the localization algorithm creates a map of the expected RSS at every point on stage using Eq. 2.1. An example RSS map is given in Fig 4.1, where the antenna is located at the downstage right corner of the stage (0.0 m, 0.0 m, 2.0 m) and the system calibration location is (0.5 m, 0.5 m, 1.6 m). All RSS (and subsequent TDOA) values have been normalized to allow for direct comparison.

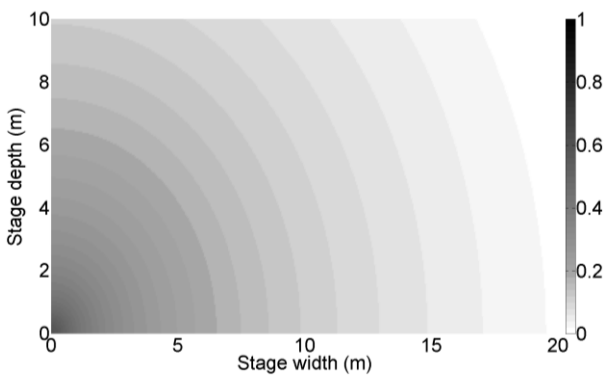


Fig 4.1 Received signal strength (RSS) map for a single antenna at (0.0 m, 0.0 m, 2.0 m) and a calibration location (0.5 m, 0.5 m, 1.6 m)

The RSS map highlights the drawback of single-antenna localization: there is no distinction between which direction away from the receiver the transmitter has moved (i.e. it is impossible to judge whether a transmitter is 10 m away along the stage depth, length or combination of both). Localization is more accurate the further the transmitter is away from the antenna as the RSS map begins to represent a plane wave on stage. If a performer tends to be limited to the downstage area (assumed to be the first 2 m of the stage depth), single-antenna RSS may be acceptable (Fig 4.2).

The single-antenna system is evaluated by calculating the shift in RSS from downstage to upstage (over the full 10 m stage depth) at various points along the stage width (Table 4.1). This shift is compared to the maximum RSS value on stage and a percentage of maximum value is determined. A lower range percentage means more reliable tracking across the stage. The same analysis, if applied to the downstage 2 m gives performance indicated in Table 4.2.

The full upstage-downstage range calculations indicate that over the first half of the stage nearest the antenna the system can't accurately track a performer. On the far side of the stage, however, there are fairly consistent RSS values from upstage to downstage, allowing for localization. When only analyzing the 2 m furthest downstage, beyond 1 m away from the antenna shows high accuracy, indicating that this technique is acceptable if only the downstage area is of interest.

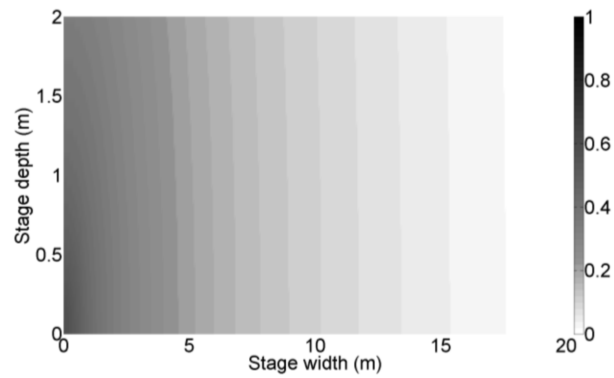


Fig 4.2 Received signal strength (RSS) map for an antenna (0.0 m, 0.0 m, 2.0 m) and calibration location (0.5 m, 0.5 m, 1.6 m), over the first 2 m of stage depth

Horizontal position on stage (m)	1.0	4.0	10.0	16.0	19.0
Upstage-downstage range (% of maximum value)	55.5	24.5	8.6	4.1	3.0

Table 4.1 RSS range percentages for various horizontal locations and calculated over the entire stage depth

Horizontal position on stage (m)	1.0	4.0	10.0	16.0	19.0
Upstage-downstage range (% of maximum value)	19.1	2.8	0.50	0.20	0.14

Table 4.2 RSS range percentages for various horizontal locations and calculated over the first 2 m of stage depth

4.2. Two receivers

Typical wireless microphone systems at professional live events utilize two antennas connected to one or more receivers, commonly through an active splitter system [9]. The function of the second reception point is to enable antenna diversity. Two antennas provide benefits in terms of audio quality and reliability, but what benefits do they give in terms of performer tracking?

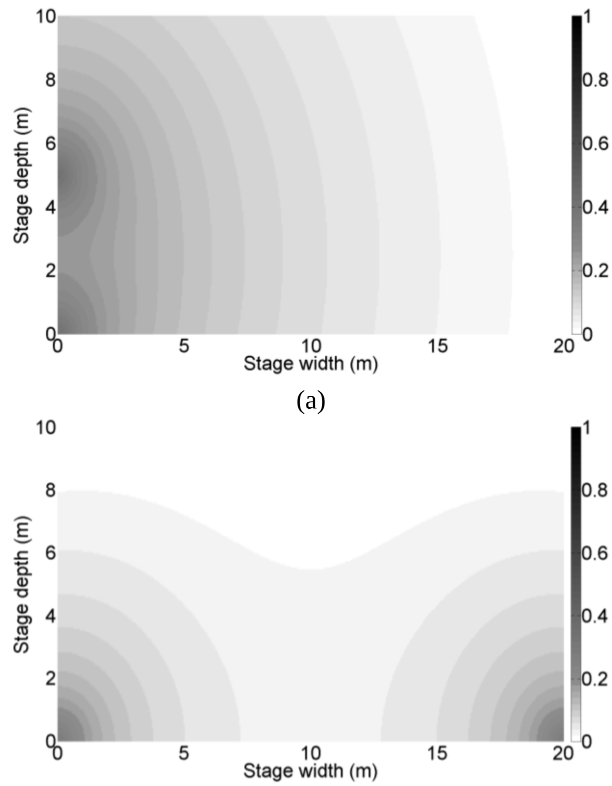
4.2.1. Received signal strength (RSS)

As with single-antenna tracking, perhaps the simplest form of dual-antenna tracking involves received signal strength (RSS). Taking onboard the system from 4.1 (where a calibration step was required), the system is calibrated as before where each antenna sets its reference signal strength at a short distance (the calibration position is equidistant from the antennas). The combined RSS is predicted over all stage locations, as before. Systems with both antennas at the same side of the stage, spaced at 5 m (Fig. 4.3a) and with antennas at opposite downstage edges (Fig. 4.3b) are examined. The performance analysis was repeated, with results given in Tables 4.3 and 4.4.

When both antennas are placed on the same side of the stage (as is the case in most applications) RSS gives precise mapping across the stage width, only with the loss of accuracy at the far upstage edge (Fig. 4.3a). Antennas at opposite sides of the stage give similar problems to that of the single antenna. Downstage, tracking is very accurate, but as a performer moves upstage this accuracy is lost (Fig. 4.3b). A general trend for RSS-style localization is that to achieve accurate horizontal stage tracking, the antennas need to be aligned across the stage depth dimension.

With antenna spacing maximized, this upstage accuracy issue is largely avoided (Fig. 4.4 and Table 4.5). The majority of events, however, won't or can't utilize the full stage depth for antenna placement, so this may not be a viable solution.

As with the single-antenna system, both dual-antenna configurations with RSS-based localization perform well along the downstage edge of a stage (ignoring the effects of reflections, of course). The configuration with one antenna on each downstage corner of a stage performs far worse than the single antenna approach, giving minimal horizontal localization accuracy (but good depth localization). The spaced stage right configurations, however, give significant improvement over a single-antenna system whereby accuracy is maintained across the stage width and depth. Issues still persist near the stage right edge, but this may not be a huge problem, depending on the performance area.



(b)

Fig. 4.3 Received signal strength (RSS) map for two antennas at (0.0 m, 0.0 m, 2.0 m) and: (a) (0.0, 5.0, 2.0) or (b) (20.0, 0.0, 2.0), with calibration locations (0.0 m, 2.5 m, 1.6 m) and (10.0 m, 0.0 m, 1.6 m), respectively

Horizontal position on stage (m)	1.0	4.0	10.0	16.0	19.0
Upstage-downstage range (% of maximum value)	39.8	15.3	5.6	2.7	2.0

Table 4.3 RSS range percentages for various horizontal locations (antennas spaced along stage right dimension)

Horizontal position on stage (m)	1.0	4.0	10.0	16.0	19.0
Upstage-downstage range (% of maximum value)	66.0	26.3	11.6	26.3	66.0

Table 4.4 RSS range percentages for various horizontal locations (antennas spaced at opposite downstage edges)

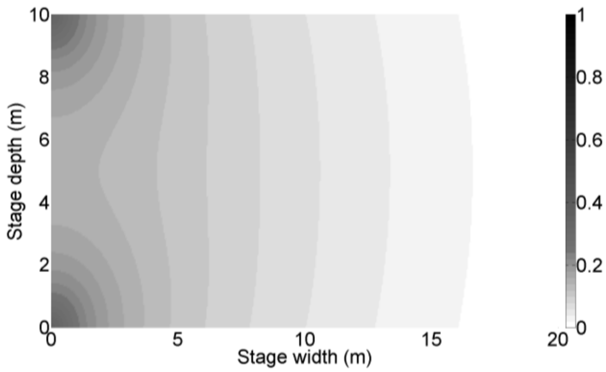


Fig. 4.4 Received signal strength (RSS) map for two antennas at (0.0 m, 0.0 m, 2.0 m) and (0.0, 10.0, 2.0), with calibration location (0.5 m, 0.5 m, 1.6 m)

Horizontal position on stage (m)	**1.0**	**4.0**	**10.0**	**16.0**	**19.0**
Upstage-downstage range (% of maximum value)	30.1	3.3	1.3	0.94	0.75

Table 4.5 RSS range percentages for various horizontal locations (antennas spaced at opposite stage right edges)

4.2.2. Time difference of arrival (TDOA)

Utilizing RSS for performer tracking is reasonable with two appropriately-placed antennas as long as performers don't regularly move far upstage. Previous research into RSS shows degraded accuracy due to reflections [3], therefore another solution may be required.

Disregarding the signal processing capabilities required (for the time being), time difference of arrival (TDOA) is determined by the peak in cross-correlation between two received signals (as discussed in section 2.3). Even if strong reflections exist at both antennas, the cross-correlation function is likely to retain a maximum value at the sample corresponding to the inter-antenna spacing. A quick test of this assumption is described later in this section.

TDOA is determined using the cross-correlation of two received signals, assuming an anechoic environment with two antennas located at (0.0 m, 0.0 m, 2.0 m) and (0.0 m, 5.0 m, 2.0 m) and a single transmitter located at (12.0 m, 1.4 m, 1.6 m). For illustrative purposes, the received signals are represented by impulses (Fig. 4.5).

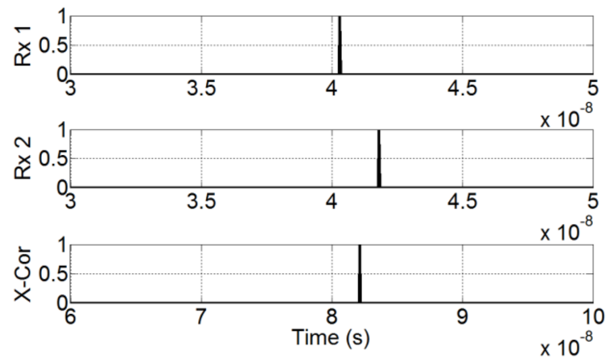


Fig 4.5 Example of cross-correlation based on received signals at two antennas located at (0.0 m, 0.0 m, 2.0 m) and (0.0 m, 5.0 m, 2.0 m) and a transmitter located at (12.0 m, 1.4 m, 1.6 m)

TDOA is found by locating the maximum value of the cross correlation vector and determining its offset from the central index. This difference is divided by the sample rate, which gives the TDOA in seconds. In this scenario, the TDOA is 1.5 ns. TDOA is updated by analyzing successive windows of the received signals.

To test the issue of reflections, a simplistic situation was modeled, whereby three strong reflections are inserted into the simulation at (5.0 m, 10.0 m, 1.5 m), (21.0 m, 4.0 m, 2.2 m) and (-1.0 m, 8.0 m, 0.6 m). The reflection coefficients are 0.95, 0.50 and 0.78, respectively.

The same TDOA scenario from Fig. 4.5 was repeated with the received signals and the cross-correlation vector shown in Fig. 4.6.

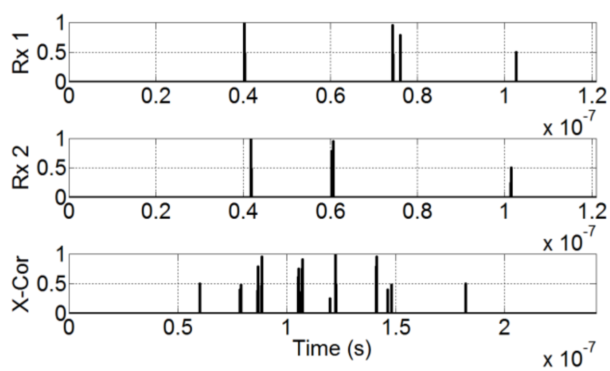
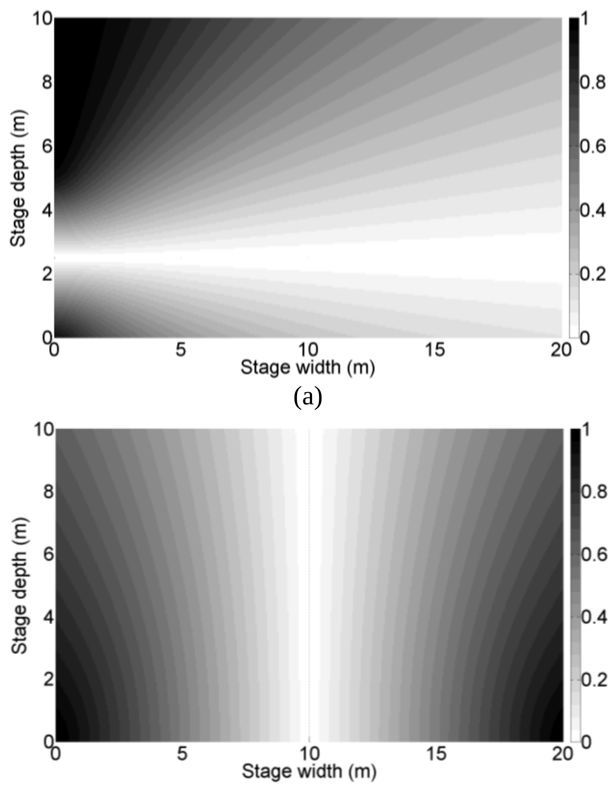


Fig 4.6 Example of cross-correlation based on received signals at two antennas located at (0.0 m, 0.0 m, 2.0 m) and (0.0 m, 5.0 m, 2.0 m) and a transmitter located at (12.0 m, 1.4 m, 1.6 m) with three reflections corrupting the received signals

As with the anechoic case, the system correctly identifies the TDOA as 1.5 ns, indicating that this level of reflective interference doesn't create a problem.

TDOA localization is similar in approach to RSS in that predicted values are mapped to show the corresponding possible transmitted locations (for illustrative purposes only). The one distinct advantage here is that no calibration is necessary since the measurements are relative to each other. This is tested for the two configurations used for dual-antenna RSS systems with results given in Fig. 4.7 and Tables 4.6 and 4.7.



(a)

(b)

Fig. 4.7 TDOA map for two antennas at (0.0 m, 0.0 m, 2.0 m) and: (a) (0.0, 5.0, 2.0) or (b) (20.0, 0.0, 2.0)

Horizontal position on stage (m)	1.0	4.0	10.0	16.0	19.0
Upstage-downstage range (% of maximum value)	99.0	87.4	59.3	42.2	36.5

Table 4.6 RSS range percentages for various horizontal locations (antennas spaced along stage right dimension)

Horizontal position on stage (m)	1.0	4.0	10.0	16.0	19.0
Upstage-downstage range (% of maximum value)	33.2	19.9	0	19.9	33.2

Table 4.7 RSS range percentages for various horizontal locations (antennas spaced at opposite downstage edges)

The spaced stage-right configuration (which gives reasonable tracking results for RSS) is by far the worst performing system tested. Time differences between antennas become greatest along the depth dimension of the stage and vary minimally horizontally. This is acceptable for an upstage-downstage tracking system, but not for width tracking. The opposite downstage positions perform well, especially in the downstage half of the stage depth. This positioning of antennas can pose practical issues, though, which is discussed in section 5.

4.2.3. Comparison of potential systems

The calculated tracking errors were plotted as a function of horizontal stage position and system configuration (Fig. 4.8) to summarize the potential performance of the tested systems.

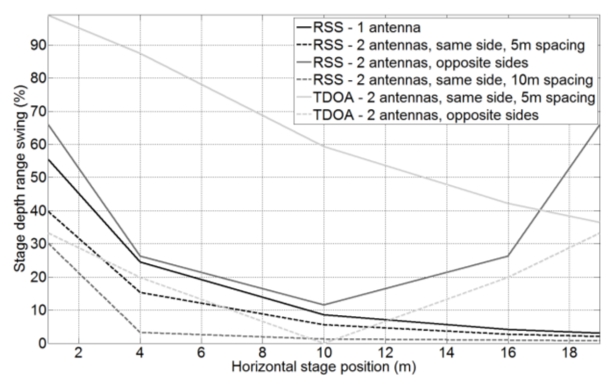


Fig 4.8 calculated range percentages for various horizontal locations using various system configurations (anechoic environment)

This comparison highlights the strength and weaknesses of each system. TDOA with antennas at the same side of the stage is clearly unacceptable, but the configuration with antennas at opposite sides gives progressively better performance towards center stage. RSS performs best when antenna spacing is maximized, where the single antenna system can be thought of as a dual antenna system with no spacing.

Of course, this analysis is based on a perfectly anechoic (best case) environment, which is highly unlikely to exist in practice. Section 4.4 explores the influence of reflections on tracking performance.

4.3. Hybrid technique possibilities

The RSS and TDOA systems explored in the previous sections highlight a number of advantages and disadvantages. Clearly, a dual-antenna system is ideal for antenna diversity reasons. As it is likely impractical to place antennas at opposite sides of the stage, systems consisting of spaced antennas on one side of the stage are of particular interest.

RSS tests on such systems indicate good horizontal tracking across the stage width while TDOA tests show good stage depth tracking (this, of course, disregards reflections, which may cause significant issues). If these two methods were implemented on the same antenna system, tracking across the width and depth of the stage should be possible (and quite accurate).

RSS tracking could be used for stereo panning purposes and TDOA tracking could provide depth effects such as level attenuation or increased reverberation. This, of course, is assuming suitable hardware was available to properly perform the TDOA calculations.

4.4. The effect of strong reflections

The preceding discussions assume an anechoic RF environment, which is unlikely to occur in practice. There are typically large metallic surfaces at points around a stage than can reflect RF signals, corrupting the received signals. The key question here is whether strong reflections diminish the performance of tracking methods. In classical tracking systems reflections are well-known to cause issues [3].

A practical experiment was conducted in a large lecture theater at the University of Derby’s Markeaton Street building, with “stage” dimensions of 9.8 m x 6.5 m. Two omnidirectional antennas were set up at opposite sides of the room at the front of the designated stage area, 0.7 m from their respective side wall. A 5 x 3 point grid was laid out across the stage area with 2 m spacing between each point.

First, a wireless microphone transmitting at 608.500 MHz was mounted to a stand and placed at each grid location, in turn. Output from each antenna was monitored on a spectrum analyzer and signal strength was noted. The experiment was then repeated with the microphone held by an individual facing out towards the audience area. Results from these experiments are shown in Fig 4.9.

For confidence in system performance, the resulting plots should be very similar to those predicted by the simulation for a similar configuration (Fig. 4.3b). There are some similar attributes, but there are clearly issues. Looking at the system with no human inference (top plot in Fig. 4.9), the two lobed pattern in visible, but with an odd shaped lobe on the left side of the plot. This is due to the presence of a concert grand piano at that corner of the stage area. It can be concluded that the heavy metal strings and large surfaces of the piano caused a fair amount of reflections, degrading the performance of the tracking system.

Introducing a human into the system (bottom plot in Fig. 4.9) shows even more reflection-related issues. This highlights a serious issue for RSS tracking systems. The human body can attenuate an RF signal by over 25 dB, depending on the placement of the microphone and the orientation of the performer relative to the antennas [9]. This is an important issue to address before a system of this variety is practical and will be discussed further in section 5.1.

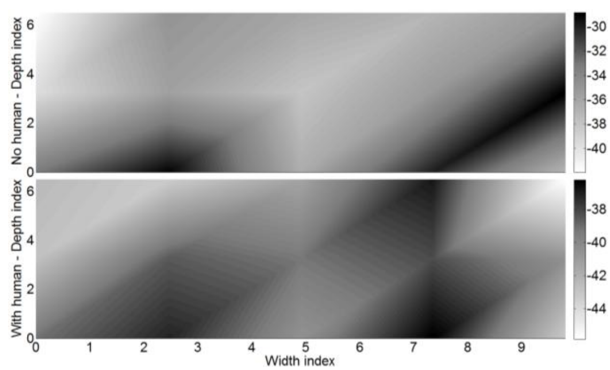


Fig 4.9 Received signal strength (RSS) measurements for two antennas at (0.7 m, 0.0 m, 2.0 m) and (9.1 m, 0.0 m, 2.0 m) with no human interference (top) and with human interference (bottom)

5. PRACTICAL DISCUSSION

There are many practical considerations regarding implementation of the technology discussed in the previous section. Certain issues are relevant to the implementation of the tracking system, in terms of the hardware and software used. Other issues arise due to the practicality of embedding such a system into the existing infrastructure of a live event in a way that minimizes uptake costs and configuration requirements. The forthcoming sections discuss some of the key points stemming from these necessary considerations.

5.1. Implementation issues

The first things that must be considered regarding system implementation are the capabilities of the hardware the system is meant to be embedded within. Devices capable of sample rates in the gigahertz range are extremely expensive and certainly not designed to handle exposure to the elements at live events (and the transportation between). Although years from now, this technology may be more practical, at the moment TDOA must be eliminated from consideration.

This leaves RSS as the method of interest for a performer tracking system. Again looking at the hardware, there is a question of how many wireless microphone signals can be tracked at any one time. To track any number of performers, a series of filters would need to be implemented to focus on the signal level over a narrow frequency band. If the tracking system were to be embedded within the existing wireless microphone receivers, this wouldn't be a problem as signal strength is already monitored within these devices. This would be the preferred route for such a system: integration within the existing receivers.

The central issue concerning implementation using RSS is the effect of reflections, as discussed in section 4.4. The practical experiment highlighted the fact that RSS is strongly influenced by objects in the environment, with human body being one of the strongest influences. A performer is unlikely to remain at a constant orientation to the audience, but will turn various directions during a performance. This will lead to a varying level of signal attenuation due to blockage from the performer's body. If the RSS system were based on a mapping system of expected signal strengths on the stage, there would be significant issues causing the system to indicate that the performer has suddenly jumped many meters away from the antennas when he/she has simply turned away. A potential solution to this could be to apply a wide rolling average filter to the incoming signal to smooth out these issues, but this would assume the performer would continue to rotate and not stay in one position for too long. This isn't likely to be a realistic assumption.

Alternatively, the system could be calibrated to operate using the relative signal difference between the two antennas. So long as the antennas are in the same general area of the stage, performer rotation should affect the signal strength roughly equally at both antennas, giving consistent relative signal strength between the two.

It is crucial to resolve these issues. Otherwise a tracking system of this sort is simply impractical for use in the real world. Of course, ways around these issues exist such as additional antennas, expensive signal analysis hardware and specialized wearable tracking units, but these would go against the primary thrust of this work to realize a system within the existing infrastructure.

5.2. Live event industry issues

In addition to the technical issues inherent in such a system, careful considerations must be made in regards to the needs at live events. Uptake of entirely new technology in the industry can be slow, especially if significant investment is required into dedicated hardware. Besides cost implications, an entirely new system may require reconfiguring a company's standard systems and training employees. It would be ideal for a tracking system to utilize existing hardware so that it fits within the existing infrastructure, limiting uptake costs, necessary training and reconfiguration.

In regards to current industry engineers' uptake of such technology, some important considerations arise. In general, factors that would make performer tracking practical are easy set up, predictability and better experience for the spectators.

Simple setup is crucial for performer tracking. The fast-paced production environment leaves little time for testing system components. Setup time should be minimal with calibration being semi-automated. Technicians should not need any advanced knowledge of RF systems to make tracking fully functional. Crucially, the RF tracker will need to be able to compensate for less than optimal antenna placement for it to be viable in touring productions.

Predictability of the tracking system results will be required for many different situations. The way the RF tracking interacts with the sound system may need to be adjusted due to speaker placement or venue acoustics. Hard-panned audio setups could create the desired effect in a narrow venue, but in a wide venue may cause parts of the audience to be unable to hear the performer in a wider space.

Concerning the practicality of the proposed systems, there are a number of things to keep in mind. First, it is standard practice to place RF antennas on the same side of stage as the monitor mix position. Placing an antenna at the opposite side of stage requires a significant amount of coaxial cable as well as signal boosters to compensate for signal loss. This is unlikely to be a popular solution. Additionally, since space is often at a premium on the stage wings, antenna placement can be limited, therefore inter-unit spacing may not be as much as ideally required (but 5 m spacing isn't unreasonable).

Overall, performer tracking can be very useful at live events, but the technology must be implemented with practicality in mind. This translates to minimal new hardware and quick calibration procedures.

6. CONCLUSIONS AND FUTURE WORK

In the age of ever-expanding convenience due to new and improved digital systems, it is only a matter of time before many functions currently done manually at live events will be automated (at least in addition to those that already are automated). This is not to say the live engineer will no longer be needed. Such systems would enhance the audience experience by extending the capabilities of the sound and lighting systems, freeing engineers to focus on the creative aspects of their role.

The purpose of this research is to explore the possibilities of using existing RF signals from wireless microphones to accurately track performers on stage. Professional practice dictates the use of two antennas for wireless systems, which allows for two possible tracking techniques: received signal strength (RSS) and time difference of arrival (TDOA). It is more realistic to have antennas positioned on the same side of a stage (due to extensive signal loss in the coaxial cable needed to run cross-stage [9]), therefore RSS and TDOA systems of this variety are of particular interest. TDOA, however, isn't currently practical due to sampling rate limitations of existing affordable equipment.

Simulations show that RSS systems give accurate tracking over the stage width and depth, respectively, but issues did come to light after practical experiments due to strong reflections from the surroundings and high body attenuation.

If the technological issues presented in section 5 were to be resolved, there could be many applications of such a system. Applications for such systems include stereo panning, surround sound effects, feedback suppression (when a performer comes too close to a loudspeaker), adaptive monitor mixes and follow-spot automation. These RF-based tracking systems are much more practical than motion-based tracking as they utilize existing equipment present at most professional live events.

A significant amount of research is clearly needed to take this concept forward (and it is also likely that the required practical technology may still be a number of years off). More experiments must be conducted in real-world performance environments with industry-standard hardware and techniques must be developed to limit the impact of reflections and body attenuation on signal strength. Only then will it be clear whether such a system can be put into use in practice or whether this is simply impractical at this moment in time.

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