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Spatial Diversity in Signal Strength based WLAN Location Determination Systems[1]

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ABSTRACT

Literature indicates that spatial diversity can be utilized to compensate channel uncertainties such as multipath fading. Therefore, in this paper, spatial diversity is exploited for locating stationary and mobile objects in the indoor environment. First, space diversity technique is introduced for small scale motion and temporal variation compensation of received signal strength and it is demonstrated analytically that it enhances location accuracy. Small scale motion refers to movements of the transmitter and/or the receiver of the order of sub-wavelengths while temporal effects refer to environmental variations with time. A novel metric is introduced for selection combining in order to improve location accuracy through the addition of spatial diversity upon two available location determination schemes. The results are evaluated experimentally against single antenna system for reception by using low cost wireless RF devices such as motes. Alternatively, the impact of the number of location determination devices in a probabilistic WLAN network based on pre-profiling of signal strength is analyzed and it is demonstrated analytically that location accuracy improves with the number of receivers used. Spatial diversity in terms of the antenna spacing of 2λ is evaluated and shown to provide a reduction in location determination error between 30 and 40% when compared to a single antenna system.

Keywords

Geo-location, WLAN Location Determination, Spatial Diversity, Location Accuracy

1. INTRODUCTION

In industrial and service sectors, real-time locating and tracking of assets and personnel is fast becoming a necessity. Several technologies have been developed and implemented with varying degrees of success. While efforts started with infrared and ultrasonic technologies [1] [2], it was recognized that use of radio frequency (RF) technologies, being easily scalable and deployable, was the option of choice [3] due to low cost and minimal safety concerns due to absence of wiring. Subsequently, different location determination schemes in the RF domain were developed which include time of arrival (TOA), time difference of arrival (TDOA), angle of arrival (AOA), and received signal strength (RSSI) etc. [4].

Towards this end, time and angle based systems have been developed but they ([4]) are difficult to implement owing to requirement for specialized hardware. Signal strength based systems, on the other hand, can be used on all RF networks without additional hardware and therefore being addressed by many researchers as a cost effective solution for location determination.

The fundamental premise of signal strength-based location determination is that received signal strength indicator (RSSI) at a receiver is a function of the location of the transmitter. For the past few years, considerable interest has evolved in using RSSI for location determination. RADAR and HORUS are examples of prior work on WLAN based indoor location determination. RADAR was developed as a deterministic location determination system based on average signal strength received from each reference location [5]. On the other hand, HORUS [6] uses a probabilistic algorithm for location determination.

A major challenge facing WLAN location determination is that signal strength of received radio signals is a dynamic parameter and varies widely with changes in the environment due to fading, shadowing etc. The factors include both small-scale and temporal effects, and such variation puts a limit on the resolution achievable by the location determination system.

Diversity has been a well-researched topic in the field of communications with the view of combating fading. It involves combining multiple uncorrelated signal envelopes in order to obtain a signal with a higher signal to noise ratio (SNR). Several methods for signal combining have been developed targeting SNR improvement. For location determination, achieving higher SNR does not automatically result in better accuracy unless received signal strength is consistent.

In the proposed work, it is demonstrated that spatial diversity can be employed to effectively reduce the variation in received signal strength values and as a result, improved accuracy is achieved in location determination. A new metric is

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introduced for selection combining and shown to reduce variance in signal strength when used with spatial diversity. The combination of spatial diversity with selection combining is shown to enhance the location accuracy of objects or assets. The impact of the number of receivers on location determination accuracy is analyzed and it is shown analytically that diversity techniques provide an efficient alternative for compensation of small scale and temporal variations and thus locating objects accurately. It is also presented that, for a given number of receivers, a system using diversity techniques with the proposed selection combining will perform better than a system without diversity. Experimental results are included by using wireless UMR motes where highly satisfactory results are demonstrated, which indeed verifies our theoretical conjecture. Therefore, we show that by using spatial diversity the cost is minimized while achieving the desired location accuracy.

2. BACKGROUND

In order to proceed, the following definitions are required. Subsequently, an overview of spatial diversity is discussed.

2.1 Definitions

RSSI (Received Signal Strength Indication): The average received signal strength at a given receiver during the reception of a packet, expressed in dBm, is known as *RSSI*.

Diversity: The use of multiple signal sources in order to improve the quality of the received signal is known as *diversity*. The different signal sources are referred to as *diversity branches.*

Spatial Diversity: An antenna configuration of two or more signal sources that are physically spaced apart (spatially diverse) to combat signal fading is known as *Spatial Diversity*.

Uncorrelated fading envelopes: When a diversity scheme is capable of ensuring minimal correlation between the received signal strength values from multiple input signal sources (multiple antennas in case of spatial diversity), such a scheme is said to result in *uncorrelated fading envelopes*. When the input channels in a diversity scheme are uncorrelated, effective mitigation of fading can be accomplished.

Selection Combining: The method of selecting one out of multiple signal sources in a diversity scheme by using SNR (select the one with higher SNR) as a criterion is known as *Selection Combining*.

In the proposed approach, the SNR criterion is replaced by *RSSI* (select the one with higher RSSI) since RSSI, and not SNR, is a representative function of transmitter location.

2.2 Overview of Spatial Diversity

The variations in signal strength can be classified into large-scale, small-scale and temporal variations [6]. Signal strength dependent location determination is based on large-scale variations of signal strength with distance, since this allows distinction between different locations. Small-scale variations in signal strength are caused by asset movements of the order of a fraction of a wavelength and are detrimental to accuracy in location determination. Additionally, temporal variations happen over time due to human activity and environmental changes. In other words, the error in both small-scale and temporal variations in terms of significant reduction in received signal strength is caused by destructive fading occurring at the receiver from multiple paths. To combat such fading of wireless signals, multiple uncorrelated fading channels are employed at each receiver.

Motivation for use of diversity techniques stems from the fact that the probability of simultaneous deep fading occurring on two uncorrelated fading envelopes is much lower than the probability of a deep fading occurring on a single branch system. Thus, employing a new selection combining approach on top of any diversity technique which assures sufficiently uncorrelated channels will reduce the variance in signal strength.

The normalized correlation coefficient $\rho(\xi)$ between the two fading envelopes from the input sources provided by spatial diversity is expressed as a function of antenna separation [8] as

$$\rho(\xi) \cong J_0^2(2\pi\xi) \qquad (1)$$

where ξ is the separation between two antennas expressed in terms of multiples of the wavelength in use, in our case, 2.4 GHz, and J_0 is the Bessel function of the first kind and order zero.

From (1), it is clear that for a separation of 2λ between the antenna elements, the correlation coefficient is around 0.025 and hence the fading envelopes can be shown to be uncorrelated. Further, in [9] experimental results at 1800 MHz indicate that 2λ is an acceptable value of separation to ensure almost totally uncorrelated channels.

Hence, in the proposed work, spatial separation of 2λ (25 cms for 2.4 GHz) is used to ensure uncorrelated fading channels. Section III shows how the proposed selection combining, employed with a two-branch diversity system lowers the variation in RSSI. Consequently, it will be proven that reduced variance in signal strength renders improved location accuracy.

3. PROPOSED METHODOLOGY

We prove that use of selection combining over two uncorrelated channels results in reduced variance in signal strength provided the selection combining is performed using the appropriate metric and in an adequate manner. Alternatively, it is demonstrated that by increasing the number of receivers the accuracy can be further enhanced but with an increased cost. Actual implementation spatial diversity is detailed. RSSI values from the transmitter are used to arrive at an estimate of its location. An asset location tracking system is developed to determine whether the located asset is moving or stationary. Averaging of consecutive estimated locations of the transmitter is performed to improve location accuracy. For mobile assets, a prediction scheme is developed to identify their future location for tracking applications. First, the source of errors in locating objects is discussed.

3.1 Source of Location Determination Errors

The work described in [7] discusses location accuracy for identifying two given points with one receiver. Let us consider this basic system as shown in Fig. 1(a) for error analysis. Initially, a transmitter is placed at location A and made to transmit repeatedly for a period of time, during which the RSSI values observed at the receiver are recorded. These values are now stored as a signal strength distribution with probability density function (PDF) f_A. Similarly, the transmitter is placed at location A and made to transmit for the same period of time and the observed RSSI values at the receiver are stored as a probabilistic distribution with the PDF f_B. This completes the offline phase.

In the online phase, the transmitter is placed at location A and made to transmit once. Let us assume this transmission is collected at the receiver with a RSSI value of S_A. Now, based on the stored signal strength distributions at the receiver from a transmitter placed at locations A and B, the likelihood of the transmission having originated from a transmitter located at A or B can be evaluated. Let $f_A(S_A)$ and $f_B(S_A)$ be the values on the PDFs f_A and f_B respectively at the RSSI value of S_A. Now, if $f_B(S_A) > f_A(S_A)$ for the observed RSSI value of S_A, then the location determination system would wrongly decide that the transmission has originated from location B. Such a case is shown as example in Fig. 1 (b). The integral of $f_A(S_A)$ over the range of S_A for which $f_B(S_A) > f_A(S_A)$ gives the probability of wrong identification of a transmission from location A as if it is originating from the location B. This probability is expressed by the shaded area in Fig. 1 (b).

This probability can be mathematically expressed as

$$P_1^{A\to B} = P\left(f_A(S_A) < f_B(S_A)\right) \tag{2}$$

where $P_1^{A\to B}$ is the probability of wrongly identifying a transmission arriving from location A as if it is arriving from location B while using one receiver for distinction, S_A, the ob

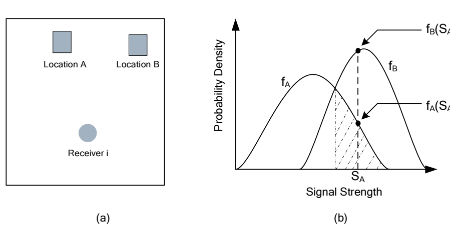

Fig. 1. (a) Two locations A and B and a single receiver i. (b) Probability density functions of signal strength received from each location at the receiver.

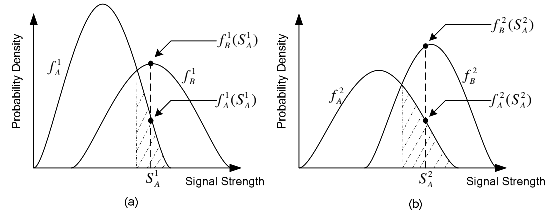

Fig. 2. Probability Density Functions from locations A and B at (a) Receiver 1 and (b) Receiver 2

served RSSI from location A is a random variable obeying the PDF f_A of the RSSI, $f_A(S_A)$ is the value of the PDF f_A at the RSSI value S_A, and $f_B(S_A)$ is the value of the PDF f_B at the RSSI value S_A.

Now let us add one more receiver to the scenario. In the offline phase, the RSSI values from a transmitter at both locations A and B observed at both receivers are individually recorded and stored as PDFs. Let f_A^1 and f_B^1 represent the PDFs of observed RSSI values at receiver 1 from locations A and B respectively and f_A^2 and f_B^2 be the PDFs of observed RSSI values at receiver 2 from locations A and B respectively. The receivers are assumed to be linked to a central server through a backbone network. The RSSI values are brought to the server for building and storing the distributions as well as computing the location in the online phase.

In the online phase, the transmitter is placed at location A and made to transmit. Let the observed signal strength values at receivers 1 and 2 be S_A^1 and S_A^2 respectively. These values follow the PDFs f_A^1 and f_A^2 respectively. Here, $f_A^1(S_A^1)$ and $f_B^1(S_A^1)$ are the values of the PDFs f_A^1 and f_B^1 at the observed RSSI value S_A^1 at receiver 1 and $f_A^2(S_A^2)$ and $f_B^2(S_A^2)$ are the values of the PDFs f_A^2 and f_B^2 at the observed RSSI value S_A^2 at receiver 2. Unlike the single receiver case, here, the product of $f_B^1(S_A^1)$ and $f_B^2(S_A^2)$ has to be greater than the product of $f_A^1(S_A^1)$ and $f_A^2(S_A^2)$ for the transmission from location A to be wrongly identified as if it is originating from location B. This probability can be represented mathematically as

$$P_2^{A\to B} = P(f_A^1(S_A^1)\bullet f_A^2(S_A^2) < f_B^1(S_A^1)\bullet f_B^2(S_A^2)) \tag{3}$$

where $P_2^{A\to B}$ is the probability of wrongly identifying a transmission from location A as originating from location B.

Now, we scale the scenario to k receivers which linked to the central server. In the offline phase, the transmitter is placed at both of the reference locations and made to transmit for a period of time. The received RSSI values on the k receivers are brought to the central server and RSSI PDFs are computed for both reference grid locations at each receiver. These PDFs are labeled as f_A^i and f_B^i where $i = 1 \cdots k$ is the receiver number and f_A^i represents the PDF of the RSSI from a transmitter placed at location A observed at receiver i and f_B^i represents the PDF of the RSSI from a transmitter placed at location B observed at receiver i. In the online phase, the transmitter is placed at location A and made to transmit. RSSI values S_A^i are received at receivers $i = 1 \cdots k$, where S_A^i follows PDF f_A^i. By induction from (3), the probability of wrongly identifying a transmission originating from location A as if it is originating from location B can now be expressed as

$$P_k^{A \to B} = P\left(\prod_{i=1}^{k} f_A^i(S_A^i) < \prod_{i=1}^{k} f_B^i(S_A^i)\right) \quad (4)$$

where $P_k^{A \to B}$ is the probability of wrongly identifying a transmission from location A as if it is coming from location B with k receivers in use, S_A^i, the RSSI observed at receiver i from location A, $f_A^i(S_A^i)$ is the value of the PDF f_A^i at the RSSI value S_A^i, and $f_B^i(S_A^i)$ is the value of the PDF f_B^i at the RSSI value S_A^i. Equation (4) quantifies probability of erroneous identification in a probabilistic location determination system. This equation helps in further analysis of the location error with and without spatial diversity and to understand the impact of number of receivers on the location accuracy, which are presented in subsequent sections. Next we present analytical results with our proposed scheme with spatial diversity where we demonstrate that spatial diversity enhances location accuracy and minimizes error.

3.2 Spatial Diversity and Location Determination

Lemma 3.1 *(Variance Reduction with Spatial Diversity):* For an indoor transmitter and receiver location pair with Rayleigh distribution of RSSI, the variance in the RSSI distribution is reduced when the proposed selection combining approach with highest RSSI being the criterion is employed on two uncorrelated fading envelopes, compared with using a single input source.

Proof: Let the PDFs of RSSI from a given transmitter location for the two uncorrelated fading channels be given by f_1 and f_2, and the cumulative distribution functions (CDF) by F_1 and F_2. It is shown in [8] that the Rayleigh distribution models the rapid amplitude fluctuations in received signal strength in the absence of a strong received component. Hence we assume the above distributions are Rayleigh in nature. Further, since the antennas providing the uncorrelated fading channels are closely located, we assume that these two antennas share similar probability distributions of RSSI for a given transmitter location. Hence,

$$f_1(S) = f_2(S); F_1(S) = F_2(S); \forall S \quad (5)$$

It is to be noted that though the distributions are similar, the signal strength at any given time from the distributions resulting from the antennas inputs is completely independent and uncorrelated (different) due to separation between them. At any given time t, let $S_1(t)$ and $S_2(t)$ represent the observed RSSI values on the two independent uncorrelated channels. By application of the proposed selection combining approach where the antenna with higher instantaneous RSSI is selected at all times, we now evolve a new RSSI parameter $S_{select}(t)$ from the RSSI values observed on the two antennas where

$$S_{select}(t) = \max(S_1(t), S_2(t)) \quad (6)$$

Let the PDF and CDF of this resulting RSSI parameter $S_{select}(t)$ from the proposed selection combining be given by f_{new} and F_{new} respectively. By definition of the cumulative distribution function, if F represents the CDF of a random variable x, for any value x_i, $F(x_i)$ represents the probability that the random variable x is less than x_i. Hence by definition, the CDF $F_{new}(S)$ represents the probability that $S_{select}(t)$ is less than S. Since, $S_{select}(t)$ is the maximum of $S_1(t)$ and $S_2(t)$, it follows that both $S_1(t)$ and $S_2(t)$ have to be less than S. Therefore,

$$F_{new}(S) = F_1(S) \bullet F_2(S) = (F_1(S))^2 \quad (7)$$

where $F_{new}(S)$ is the CDF of RSSI of the new parameter from the proposed selection combining approach and $F_1(S)$ is the CDF of RSSI on either of the input sources.

It has been shown in literature that indoor propagation follows a Rayleigh model and results in a Rayleigh distribution of received signal strength [8]. Let us assume, therefore without loss of generality, that the RSSI distributions on the input sources follow a Rayleigh distribution with a scale factor of *s*. Then the cumulative distribution function can be defined as

$$F_1(S) = 1 - e^{\frac{-S^2}{2s^2}} \quad (8)$$

Substituting (8) into (7) to get

$$F_{new}(S) = (F_s(S))^2 = 1 - 2e^{\frac{-S^2}{2s^2}} + e^{\frac{-S^2}{s^2}} \quad (9)$$

Differentiating (9) yields

$$f_{new}(S) = 2f_s(S) - f_{s/\sqrt{2}}(S) \quad (10)$$

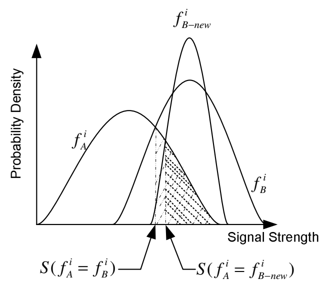

Fig. 3. Reduction in error area from spatial diversity.

where $f_{s/\sqrt{2}}(S)$ is the PDF of the Rayleigh distribution with the scale parameter of $s/\sqrt{2}$ and $f_s(S)$ is the PDF of the Rayleigh distribution with a scale parameter of s which is same as $f_1(s)$. The original distribution with a scale parameter of s and probability density function $f_1(s) = f_s(s)$ has a variance of $\sigma_1^2 = s^2 \bullet (2 - 0.5\pi) = 0.4292 \bullet s^2$ while the probabilistic distribution of the evolved RSSI parameter from the proposed selection combining method with probability density function $f_{new}(S) = 2f_s(S) - f_{s/\sqrt{2}}(S)$ can be shown to have a variance of $\sigma^2_{new} = s^2 \bullet (12+(4\sqrt{2}\text{-}9) \bullet \pi)/4 = 0.3743 \bullet s^2$ [10]. Since the scale parameter of the Rayleigh distribution, s is a real number, it is obvious that $f_{new}(S)$ has a lower variance than $f_1(S)$.

Thus, the proposed method of selection combining of two uncorrelated fading channels with similar signal strength probability distributions results in a lower variance with a factor of approximately 13 % compared to the single branch case. ■

Theorem 3.1 (Improved Location Determination with Spatial Diversity): For a given number of receivers, use of

spatial diversity renders improved location accuracy for a pre-profiling based probabilistic WLAN location determination system.

Proof: Let us consider a simple location identification system again with two locations A and B and a single receiver i. Let the signal strength distributions from both locations A and B be profiled at receiver i in the offline phase as detailed in Section III A. Let these distributions have probability density functions f^i_A and f^i_B, Let the mean of f^i_A be μ^i_A and its standard deviation be σ^i_A. Similarly, let the mean of f^i_B be μ^i_B and its standard deviation is given by σ^i_B. Let us initially assume $\mu^i_A < \mu^i_B$ (The opposite case is also handled later). We define $S(f^i_A = f^i_B)$ as the value of RSSI at which $f^i_A(S) = f^i_B(S)$.

As derived in Section III A, the probability that a transmission from location A is wrongly identified as originating from location B using only the single receiver i in the online phase is given by the probability of obtaining an RSSI value S^i_A from location A at receiver i, for which the condition $f^i_B(S^i_A) > f^i_A(S^i_A)$ is met. It can be seen from Fig. 3 that the range of S^i_A over which $f^i_B(S^i_A) > f^i_A(S^i_A)$ is given by $S(f^i_A = f^i_B) < S^i_A < \infty$. The probability of observing an RSSI value in this range at receiver i from a transmitter placed at location A is given by the integral of $f^i_A(S)$ over this interval. The integral is given as

$$P^{A\to B} = \int_{S(f^i_A = f^i_B)}^{\infty} f^i_A(S) \bullet dS \qquad (11)$$

where $P^{A\to B}$ represents the probability of identification of a transmitter at location A as if it is at location B based on the previously recorded signal strength distributions from locations A and B at receiver i, $S(f^i_A = f^i_B)$ represents the RSSI value at the receiver where the PDFs from locations A and B are equal to each other, and $f^i_A(S)$ represents the PDF of the RSSI distribution at the receiver from location A.

Now, consider that by a suitable method (in our case, spatial diversity and the proposed selection combining approach), the variance of the signal strength distribution at the receiver i from location B is reduced to σ^i_{B-new} and the PDF corresponding to this distribution is f^i_{B-new} as shown in Fig. 3 where

$$\sigma^i_{B-new} < \sigma^i_B \qquad (12)$$

We also define the RSSI value at which the PDF f^i_{B-new} meets f^i_A as $S(f^i_A = f^i_{B-new})$.

Now,

$$S(f^i_A = f^i_{B-new}) > S(f^i_A = f^i_B) \qquad (13)$$

On similar lines as in (11), the probability of wrongly identifying a transmission from location A as originating from location B can be derived as

$$P^{A\to B}_{new} = \int_{S(f^i_A = f^i_{B-new})}^{\infty} f^i_A(S) \bullet dS \qquad (14)$$

where $P^{A\to B}_{new}$ is the probability of identification of location A as location B based on the new signal strength distribution from a transmitter at location B at receiver i with reduced variance. But, from (13) and since $f^i_A(S)$ is always positive,

$$P_{new}^{A \to B} < P^{A \to B}. \quad (15)$$

Now consider the second case where $\mu_1 > \mu_2$. The error is given by

$$P^{A \to B} = \int_{-\infty}^{S(f_A^i = f_B^i)} f_A^i(S) \bullet dS \quad (16)$$

Once again, we assume that the signal strength distribution at the receiver i from location B is by suitable means (in our case, Spatial diversity), altered to f_{B-new}^i with variance σ_{B-new}^i where

$$\sigma_{B-new}^i < \sigma_B^i \quad (17)$$

Then it follows that

$$S(f_A^i = f_{B-new}^i) > S(f_A^i = f_B^i) \quad (18)$$

The error now becomes

$$P_{new}^{A \to B} = \int_{-\infty}^{S(f_A^i = f_{B-new}^i)} f_A^i(S) \bullet dS \quad (19)$$

But from (18) and since $f_A^i(S)$ is always positive $P_{new}^{A \to B} < P^{A \to B}$. Thus for both $\mu_1 > \mu_2$ and $\mu_1 < \mu_2$, the probability of location A being wrongly identified as location B is shown to be reduced if the variance of the RSSI distribution from location B is reduced. Similarly, it can be shown that reducing the variance of $f_A(S)$ will reduce the probability of wrongly identifying a transmission from an object at location B as originating from location A. Thus, reduction in variance of both distributions is proven to effectively reduce location determination error.

Lemma 3.1 indicates that the proposed method of selection combining of two uncorrelated input sources from application of spatial diversity reduces the variance of the received signal strength distributions. On the other hand, Theorem 3.1 shows that by using spatial diversity, the accuracy of determining location of an asset equipped with a transmitter is enhanced. Hence, use of spatial diversity with proposed method of selection combining is shown to reduce error in location determination in signal strength based systems. ■

Next we present how increasing the number of receivers will indeed enhance the location accuracy.

3.3 Number of receivers

Theorem 3.2 *(Location Accuracy with Number of Receivers)*: For a pre-profiled signal strength based probabilistic WLAN location determination system, the location accuracy with $k+1$ receivers is better than the location accuracy with k receivers for all $k > 0$. ■

The theorems presented above show that the accuracy improves both with spatial diversity and increasing the number of receivers. Next the proposed location determination schemes are introduced, which are built upon the known schemes, deterministic and probabilistic methods, from the literature.

3.4 Location Determination

Both probabilistic and deterministic techniques from the literature are evaluated with and without spatial diversity. We do not detail these techniques here as they are discussed in detail in [5] and [6]. The application of diversity and proposed method of selection combining on top of either technique is discussed below.

3.4.1 Diversity and Combining

There are two methods of implementing the proposed method of selection combining on top of spatial diversity using the probabilistic and deterministic schemes. It can be implemented on the hardware level using a switch for selecting the antenna with higher RSSI and using a single receiver. A second method of implementation would be at the software level, where signal strength values are recorded on two spatially separate receiver units and the higher RSSI value is selected while processing. We use the latter implementation in our testbed as it is much easier to implement, but from the view of cost-effective implementation, not requiring additional processing, the former implementation is more suitable to true real-time location determination.

In location determination without using diversity, only one receiver from each pair is used in analysis, in both the online and offline phases. By contrast, in using the system with diversity applied, each pair of receivers is viewed as a single receiver. For every packet received and RSSI reported, the maximum of the two RSSI values is taken for each pair. This software-level selection is applied before using the RSSI values for processing in both online and offline phases. Thus, the location determination algorithm becomes a higher layer of processing with the combining layer interfacing it to the RSSI readings from hardware.

4. RESULTS AND ANALYSIS

First, we discuss the testbed followed by the results and analysis.

4.1 Testbed and implementation

All experiments were conducted using G4-SSN motes developed at UMR. The wireless platform chosen was IEEE 802.15.4 PHY. All nodes are equipped with XBee pro radios from Maxstream with 18 dBm transmit power. The UMR motes with spatial diversity arrangement are shown in Fig. 4.

Two floors of the Engineering Research Laboratory (ERL) building were used for testing location accuracy. Only corridors were used in the evaluation. A total of 133 points were marked as reference grid points in a total area of 3624 sq. ft. of corridor area.

Fig. 4. UMR-SLU G4-SSN motes arranged for creating spatial diversity with a separation of 25 cms

Further, 44 test points are marked for accuracy evaluation. The offline training phase involves profiling from the 133 reference grid points. For testing accuracy, transmissions from the 44 test points are attempted to be located. Five spatially separated pairs of receivers are used for spatial diversity implementation, two on the third floor and three on the second floor. The floor plans of ERL are given in Fig. 5. Signals were able to be received across floors.

4.2 Results and Analysis

Now the results are given followed by the analysis

4.2.1 Spatial Diversity and Location determination

Accuracy results are classified into two categories based on the application of probabilistic and deterministic techniques. The mean accuracy in each case with and without applying the diversity technique is plotted against the number of receivers. In each case, the CDF of the location error is also presented. Finally, four sample points are taken and estimated locations are provided. Finally, the two techniques are compared and improvement in accuracy due to introduction of spatial diversity is demonstrated.

It can be seen from Fig. 6 that use of spatial diversity with proposed selection combining performs better than without diversity. The improvement in accuracy with diversity is significant. Further, accuracy improves with the number of receivers used, from 127 inches to 93 inches in the single branch case and from 97 inches to 63 inches in the spatial diversity case. In the deterministic method, Fig. 7 shows significant improvement in location error. The difference in error after application of spatial diversity is even more significant

Fig. 5. Floor plans of ERL third and second floor. Receiver pair positions are marked with circled squares. Transmitter positions are evenly distributed on the hallways on both floors.

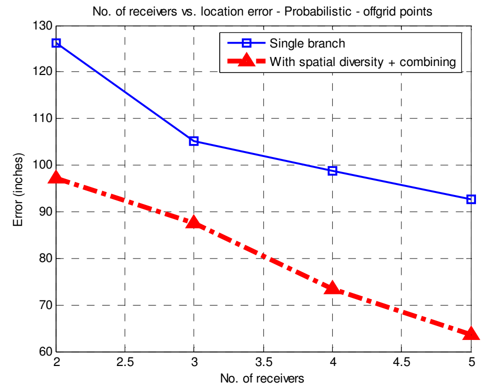

Fig. 6. Probabilistic Technique : Location error as a function of number of receivers.

with more receivers in use. For instance, with five receivers in the system, the mean errors are 87 and 60 inches respectively without and with spatial diversity

Table I presents mean, median and 90th percentile accuracy levels. Consistent improvement of 30 to 40% can be seen. Further, comparing the computational complexity, there is hardly any improvement in accuracy resulting from the application of probabilistic method over the deterministic technique.

4.2.2 Comparison of HORUS vs. Spatial Diversity

In using HORUS procedure [6] on the method including spatial diversity, only the most simplified form of HORUS is used. This includes the part of building the radio map based on representing the signal strength distributions at each receiver from each reference location as a Gaussian distribution and using these built up distributions in the online phase to locate assets (probabilistic mapping and location determination). The HORUS method consists of several other modules which, independent and irrespective of use of spatial diversity, can be applied to the location determination system to improve accuracy.

Spatial diversity in the present work [11] investigates the same concerns addressed by the perturbation method for mitigating small-scale changes.

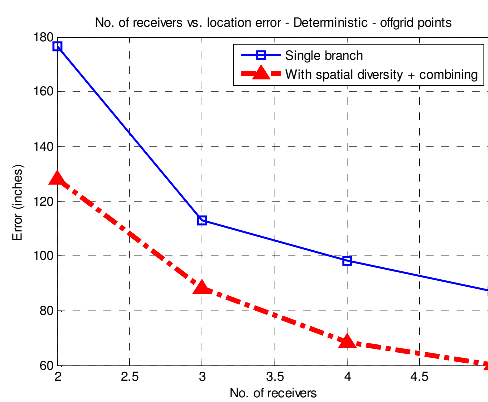

Fig. 7. Deterministic Technique. Location error as a function of number of receivers.

Table I: Summary of location determination error levels

	Mean error (inches)		Median Error (inches)		90th percentile error (inches)	
	Single Branch	Spatial Divers-ity	Single Branch	Spatial Divers-ity	Single Branch	Spatial Divers-ity
Probabilistic	93.2	**63.4**	73.9	**64.2**	205.3	**165.7**
Deterministic	87.2	**60.3**	64.2	**52.5**	200.4	**116.2**

In comparing this method with the proposed work, it is worth mentioning that while perturbation is a software level solution, our method is a hardware-level solution. Implemented with multiple antennas and selection switching, the diversity technique would add only minimal cost to the system. In terms of cost, the perturbation technique [11] appears to increase computational complexity by a factor ranging from 100% to 300 % or more depending on how many access points are perturbed and results in approximately 20 – 25 % reduction in location determination error as compared to a 35 – 40 % reduction in location error resulting from the proposed diversity technique. A comparison of the proposed work with the perturbation technique shows that while spatial diversity is analytically shown to improve location determination accuracy by combating multipath fading, the perturbation technique is a heuristic technique which does not take radio communication physics into account.

5. CONCLUSIONS

It is observed that spatial diversity with proposed method of selection combining is effective in improving accuracy in both probabilistic and deterministic location determination schemes. A novel method of improving location accuracy at minimal additional hardware cost and no additional processing has been presented and demonstrated. Comparing against the increase in the number of location sensors which resulted in improved accuracy, the use of spatial diversity is suggested to affect drastic improvements in accuracy without significantly increasing the cost of the system. In fact, improvements to the level of 30 – 40% in average location error are noticed.

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