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DOA-RSSI Multiple Subcarrier Indoor Location Estimation in MIMO-OFDM WLAN APs Structure

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Abstract: This report aims to utilize existing and future Multiple-Input Multiple-Output Orthogonal Frequency Division Multiplexing Wireless Local Area Network (MIMO-OFDM WLAN) systems characteristics-such as multiple subcarriers, multiple antennas and channel estimation characteristics-for indoor location estimation systems based on the Direction of Arrival (DOA) and Radio Signal Strength Indication (RSSI) methods. In the experimental data result, we show that location estimation accuracy performances can be increased by minimizing the multipath fading effect. This is done using multiple subcarrier frequencies over wideband frequencies to estimate one location. The proposed methods are analyzed in both a wide indoor environment and a typical room-sized office. In the experiments, WLAN terminal locations are estimated by measuring multiple subcarriers from arrays of three dipole antennas of access points (AP). This research demonstrates highly accurate, robust and hardware-free add-on software for indoor location estimations based on a MIMO-OFDM WLAN system.

Key words: Direction of Arrival (DOA) . Received Signal Strength Indication (RSSI) RSSI . Indoor location estimation method . Multipath Fading . MIMO-OFDM . WLAN

INTRODUCTION

Location awareness has many applications and is a popular research topic because it enables high-capacity communication by focusing transmitted signals toward users' locations, providing effective communication between users and safety/security in buildings where it is useful to know the location of equipment or people. Early studies in this field focused on specialized networks like infrared, Bluetooth and DC magnetic systems [1-3]. All of these systems have been shown to be highly accurate, yet there are some disadvantages, including a limited range, complex installation and high maintenance costs. Furthermore, these systems do not provide traditional data networking services. The widely used Global Positioning System (GPS) [4] is accurate in outdoor environments, but is suboptimal indoors as GPS signals are distorted by building structures.

We focus on Radio Frequency (RF) networks. These methods use traditional RF data networks supplemented by a useful location-aware system, thereby fully utilizing relevant network capabilities. There exist many techniques for building RF-based indoor location estimation systems, such as the Received Signal Strength Indication (RSSI) method [5, 6], the Time Of Arrival (TOA)/Time-Difference of Arrival (TDOA) method [7, 8] and the Direction Of Arrival (DOA) method [9, 10]

PREVIOUS WORK

Time-measurement-based methods (TOA/TDOA) have shown potential for outdoor applications, but in an indoor environment these methods are known to be susceptible to multipath fading. Furthermore, these methods require synchronization at each access point and a complex and expensive installation. A study at the Hitachi Central Research Laboratory [11] of TDOA-based systems reported approximately 4.0 m accuracy for a cumulative distribution function (CDF) error of 67% in a 16 meter by 13 meter office with six Access Points (APs), one base station and one mobile user.

The RSSI method offers lower complexity and is widely used, but it is highly influenced by multipath fading in indoor environments. In an RSSI-based RADAR project [9], the authors used a radio map of the building to build a reliable and accurate system. They conducted initial empirical measurements and signal

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propagation modeling to build a radio map of the floor of a typical office building with dimensions 43.5 m by 22.5 m. They reported 5 m accuracy for a distance CDF error of 75%. This method requires a relatively long time to complete the initial measurement setup and it can be difficult to change the layout.

DOA-based systems have also been reported to be susceptible to multipath fading. However, J. Terada [9] and H. Tsuji [10] demonstrated a promising DOA-based system. Tsuji conducted an experimental in an 8 m by 14 m office room. He used a patch array antenna comprising four element antennas at the base station, utilizing the signal strength and angle of arrival at the base station to identify each location. This method is based on the location fingerprint technique [12] and the reported accuracy was 0.5 m. Although this technique is effective, an extended time period is necessary to complete the initial measurement steps.

In this paper, our goals were twofold: keeping costs low by utilizing existing infrastructure with a minimum number of additional devices and achieving good accuracy. The recent emergence of Multiple-Input Multiple-Output Orthogonal Frequency Division Multiplexing (MIMO-OFDM) [13, 14] technologies, which may potentially suppress multipath fading effects, has brought attention to RF based indoor location systems. Furthermore, the new standards in the IEEE 802.11n Wireless Local Area Network (WLAN) manual now include these features as communications design guidelines. Therefore, evaluating the performance of location estimation systems using this technology will be critical in the future. The RSSI-based method could also potentially utilize multiple transmission subcarriers and multiple antennas to increase its performance. Therefore, in this paper we evaluate both a DOA-based method and an RSSI-based method; we excluded the TOA-based system as it requires time synchronization between the transmitter and the receiver. Fingerprinting was also avoided because it requires extra measurements over a given area or volume [12].

EXPERIMENTAL TESTBED

Our experimental areas were a LOS 10 m x 10 m area located in the Ibaraki University engineering faculty gymnasium and a 8 m x 8m area located in a seminar room. The complexity of indoor signal propagation makes it difficult to obtain a single model or formula that can fit for path loss accurately across a range of different indoor environments . Accurate path-loss can be obtained from empirical measurements for each indoor environment when tight system specifications must be met. However, for general trade-off analysis of our proposed method, our experimental test-bed would qualify for a general wide indoor environment and a typical room-sized office. Figure 1 and 2 shows the floor layout and 16 point location coordinates with four APs. The four APs are denoted A, B, C and D and the setup is shown in Table 1.

Table 1: Basis details

Frequency	2.4 GHz band
Frequency bandwidth	20 MHz
Antenna	Collinear array
	Directive gain=4 dBi
	Cable insertion loss=2.4 dB
	3 dB beam width= about 44[deg.]
	Tx. height=0.7 m, Rx. height=0.7 m
Antenna element spacing at APs	(half wavelength) Uniform linear array
Number of subcarriers	19 points are sampled over 20 MHz bandwidth at 2.39 GHz ~ 2.41 GHz: (2.39, 2.39125, 2.3925, 2.39375, 2.395, 2.395625, 2.39625, 2.3975, 2.39875, 2.4, 2.40125, 2.4025, 2.40375, 2.405, 2.405625, 2.40625, 2.4075, 2.40875, 2.41) GHz

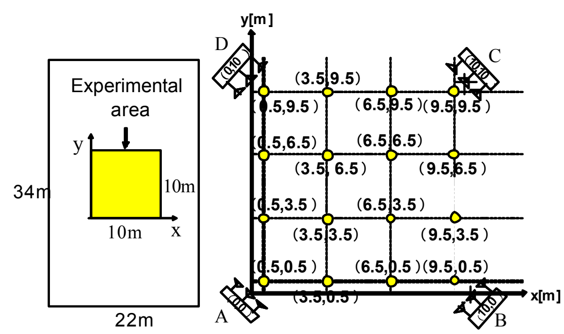

Fig. 1: The gymnasium layout and 4 APs with 16 location points

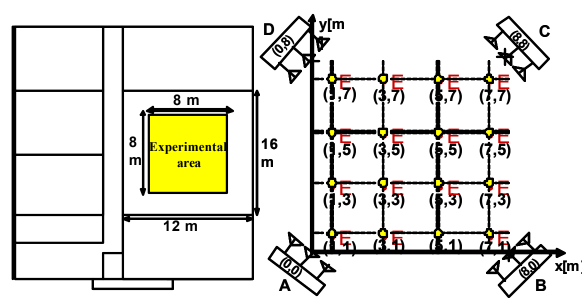

Fig. 2: Typical LOS office environment and experimental setup

A network analyzer and four dipole antennas were used. A transmitter antenna at the location point is connected to port 1 of the network analyzer. So that the receiver antennas are able to take measurements, one antenna is connected to port 2 whereas the other two were terminated with 50 ohm resistance loads. The antenna connections to port 2 and the resistor loads were lternated. The measurements at the network analyzer were averaged 16 times. We took 10 data samples and averaged their values for each location.

PROPOSED METHOD

In indoor environments, it is well-known that multipath propagation occurs and causes different parts of the transmitted signal's spectrum to be attenuated, thereby degrading DOA estimations. Theoretically, highly accurate DOA estimations can be achieved if we can distinguish the direct signal from the indirect signal or if the differential power level between the direct power and the indirect power is sufficiently large. We have to use either large antennas or a large bandwidth to achieve this. However, in practice, the frequency spectrum is a finite resource and large antennas are costly. Therefore, we came out with a solution to use the wideband and multiple antennas characteristic of MIMO-OFDM AP to mitigate the multipath fading effect for DOA and RSSI estimation. For discussion, we take one sample location from our experimental data (Tx. coordinate= (9.5,6.5) and AP A). Figure 3a shows how the signal is received at the AP. Figure 3b simulation data calculated by using following equation,

$$\theta = \frac{2\pi df}{c} - \phi_k(f) \quad (1)$$

where d is the distance between the AP and the transmitter location, f is the frequency, c is the speed of light and $\phi_k(f)$ is phase compensation of the antenna cable and given as following equation,

$$\phi_k(f) = l_k * \frac{2\pi f}{c} \quad (2)$$

where l_k is total antenna wire length. In our case the total antenna length is 4 meter. Figure 3c is the collected experimental data, Fig. 3d is S21 parameter and Fig. 3e is DOA estimation error for each subcarrier. As can be seen in Fig. 3c, by using wideband frequencies, there are substances of less and heavy multipath fading can be differentiated. Gradually straight phase value gradient represent the less multipath fading and distorted phase value gradient represent heavy multipath fading

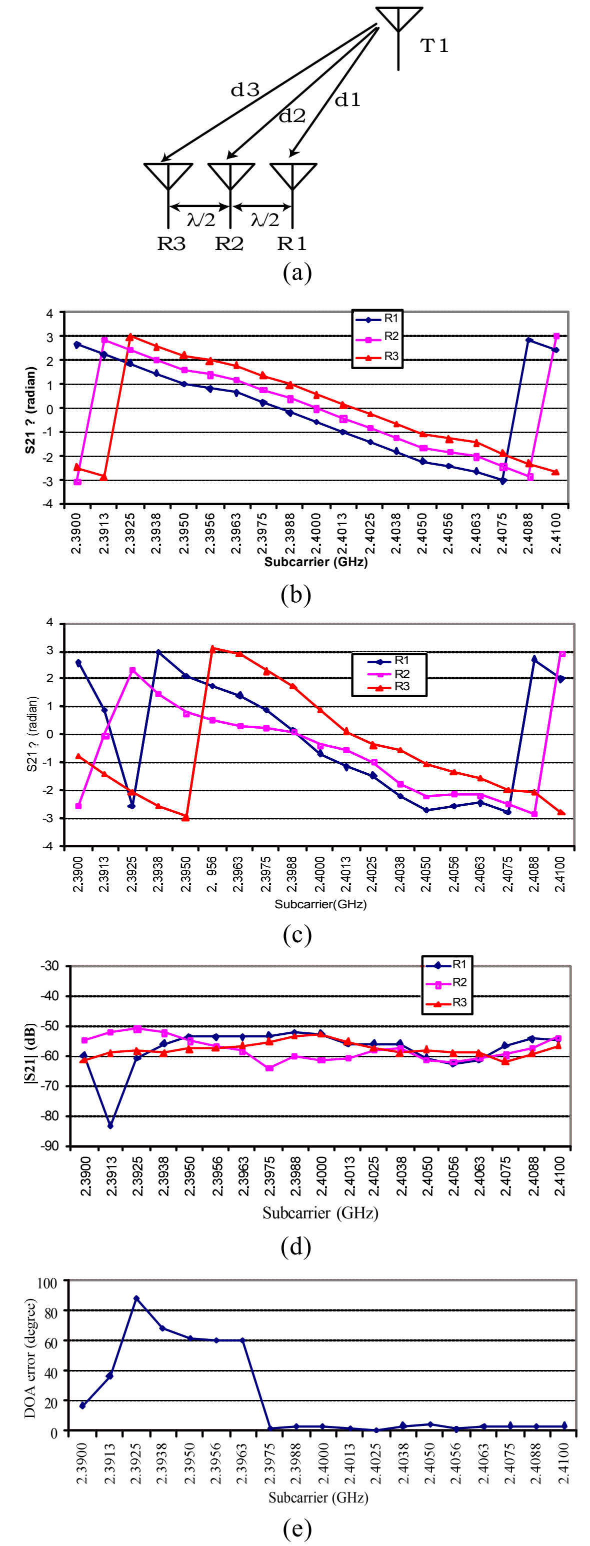

Fig. 3: DOA estimation error for each subcarrier from one sample location (Tx. coordinate=(9.5,6.5) and AP A). (a) receiving array structure (b) and (c) simulation and experimental data of received signal (d)S21 parameter (e) DOA estimation error

occurred. The comparison shows that for lower frequencies the experimental data is distorted by multipath fading, but at higher frequencies there is less distortion.

The DOA estimation process depends on the phase difference between the signals received at each antenna. Therefore, if the phase difference data is distorted then the estimation error is large. Signal distortion because of multipath fading occur randomly depends on environment. Therefore we proposed to use multiple subcarriers choose over the wideband frequencies to estimate one location [15, 16]. By utilizing this technique, we can minimize the effect of distorted signal caused by the multipath fading. Thus, increase the estimation accuracy.

In general, our proposed DOA estimation method consists of the following steps:

- From the estimated channel matrix, we calculate the correlation matrix for each subcarrier.
- From the correlation matrix, we derive the DOA estimation using beam-forming DOA algorithms [17, 18] for each subcarrier. The received power and DOA estimation are given by the θ value that maximizes the following equation, using the correlation matrix and steering vector a(θ) corresponding to the array configuration. Here, R_{hh} is the correlation matrix.

$$\max\theta = \frac{\mathbf{a}(\theta)^H \mathbf{R}_{hh} \mathbf{a}(\theta)}{\mathbf{a}(\theta)^H \mathbf{a}(\theta)} \tag{3}$$

- Median value of all DOAs from each subcarrier is calculated. By taking the median value of all of the DOA estimations, we can exclude the extraneous error values and approach the true value.
- From the DOA estimation from each AP we estimate the location. The location coordinates were estimated from the DOA results in each of the following combinations: A-B, B-C, C-D and D-A. For each location coordinate, we transmitted signals and collected data at the four arrays of antenna receivers. Figure 4 shows the method in detail.

The other three estimation coordinates were obtained with the D-A combination. The four estimation coordinates were then averaged to yield the final estimated location coordinate.

In the RSSI-based location estimation, the Friis transmission equation is used to calculate the propagation distance from the power in a received radio signal at each AP.

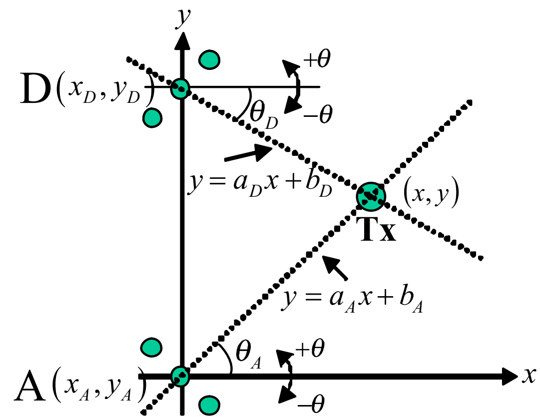

Fig. 4: The location estimation method

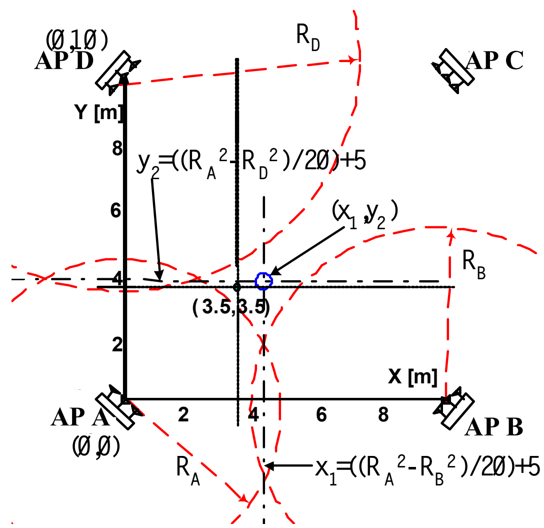

Fig. 5: RSSI-based estimation for AP AB-DA

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2 \tag{4}$$

where G_t and G_r represent the transmitter and receiver antenna gains, respectively. The received power P_r is from the experimental data. We calculate P_r using the following equation:

$$P_r = \frac{\sum_{j=1}^{M} \sum_{j=1}^{N} P_{rji}}{MN} \tag{5}$$

where M is the number of antenna elements, j represents each antenna element, i represents each subcarrier and N is the number of subcarriers (M is three and N is nineteen).

Then, the radial distance R was calculated, for each base station, as shown in Fig. 5. The coordinates for AP

A, AP B, AP C and AP D were set to (0,0), (10,0), (10,10) and (0,10) for the gymnasium or (0,0), (8,0), (8,8) and (0,8) for the seminar room. Then, we established the equation for the two intercept points between each base station estimation radius R and calculated the estimated coordinate.

RESULT AND DISCUSSION

25^{th}, 50^{th} and 75^{th} percentile Cumulative Distribution Function (CDF) of location estimation distance error at gymnasium hall and seminar room are plotted to evaluate our proposed method. Distance error is distance between true location and estimated location. 16 different locations for each indoor area spaces are used for each result to compile the CDF distance error result. We compared our proposed method, which utilizes multiple subcarriers over wideband frequencies, with a method that uses only one

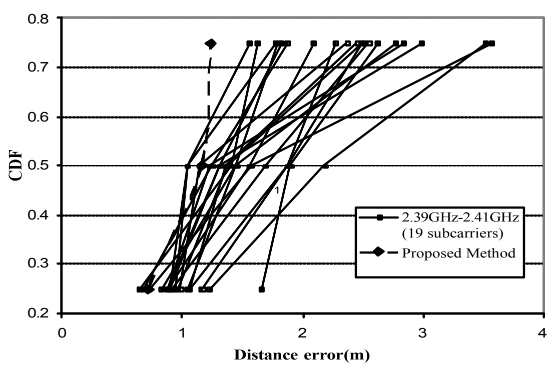

Fig. 6: Comparison of our proposed DOA location estimation method (multiple subcarriers) to other 19 subcarriers (narrowband) at Gymnasium hall

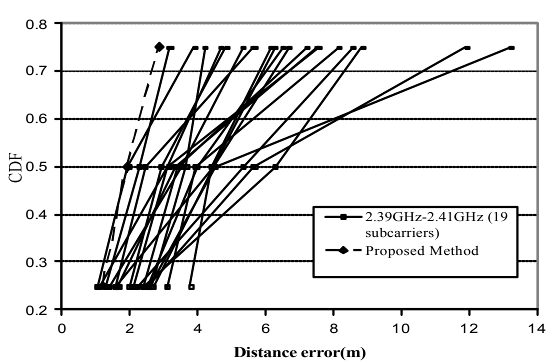

Fig. 7: Comparison of our proposed DOA location estimation method (multiple subcarriers) to other 19 subcarriers (narrowband) at seminar room

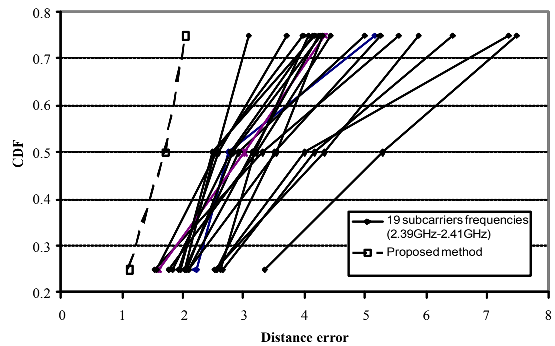

Fig. 8: Comparison of our proposed RSSI location estimation method (multiple subcarriers) to other 19 subcarriers (narrowband) at Gymnasium hall

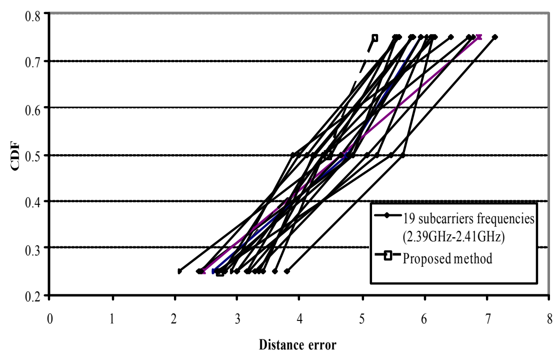

Fig. 9: Comparison of our proposed RSSI location estimation method (multiple subcarriers) to other 19 subcarriers (narrowband) at seminar room

subcarrier (narrowband frequency). We used nineteen subcarriers as listed in Table 1.

For DOA based method, in the gymnasium hall, our proposed method performs the best for the 75^{th} percentile values. In the seminar room our proposed method our proposed method performs the best for the 50^{th} and 75^{th} percentile values. In the wide space area as at gymnasium hall it has less multipath fading effect than in the seminar room. Seminar room has wider spread of distance error compared to the gymnasium hall. However, our proposed method has achieved and maintains a good accuracy result even in more congested and small room.

For RSSI based method, in the gymnasium hall, our proposed method excelled at the 25^{th}, 50^{th} and 75^{th} percentile values. In the seminar room our proposed method our proposed method performs the best for the 75^{th} percentile values. RSSI measurement is susceptible to the room size. Smaller indoor area as seminar room will produce more distortion signals. Thus decrease the location estimation accuracy. Although, compared to the proposed method in gymnasium hall, it is less accurate; however it is still outperformed single subcarrier (narrowband) based location estimation.

These results suggest that by using multiple subcarriers over wide band of frequencies for DOA and RSSI based location estimation, the location estimations can be made more accurate.

CONCLUSION

In this paper, we introduced a new and effective way to utilize multiple streaming subcarriers and multiple antennas in the now-available MIMO-OFDM RF wireless system. Our experiments lead to the following conclusions:

- Better results can be obtained by using multiple frequency subcarriers to estimate location. Our proposed method (wideband frequency) yields better results than methods that use only one subcarrier (narrowband frequency).
- For DOA-based indoor location estimation, an error distance of 1.24 m (75^{th} percentile values) in a 10 m x 10 m indoor experimental area was achieved in a 34 m x 22 m space with four APs, an error distance of 1.73 m (75^{th} percentile values) in an indoor 8 m x 8 m experimental area was achieved in a 16 m x 12 m space with four APs.
- For RSSI-based indoor location estimation, an error distance of 2.05 m (75^{th} percentile values) in a 10 m x 10 m indoor experimental area was achieved in a 34 m x 22 m space with four APs, an error distance of 5.20 m (75^{th} percentile values) in an indoor 8 m x 8 m experimental area was achieved in a 16 m x 12 m space with four APs.

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