WiFi-Based Indoor Positioning

Chouchang Yang and Huai-Rong Shao

ABSTRACT

Recently, several indoor localization solutions based on WiFi, Bluetooth, and UWB have been proposed. Due to the limitation and complexity of the indoor environment, the solution to achieve a low-cost and accurate positioning system remains open. This article presents a WiFi-based positioning technique that can improve the localization performance from the bottleneck in ToA/AoA. Unlike the traditional approaches, our proposed mechanism relaxes the need for wide signal bandwidth and large numbers of antennas by utilizing the transmission of multiple predefined messages while maintaining high-accuracy performance. The overall system structure is demonstrated by showing localization performance with respect to different numbers of messages used in 20/40 MHz bandwidth WiFi APs. Simulation results show that our WiFi-based positioning approach can achieve 1 m accuracy without any hardware change in commercial WiFi products, which is much better than the conventional solutions from both academia and industry concerning the trade-off of cost and system complexity.

INTRODUCTION

Recently, indoor positioning has attracted a lot of attention from the research as well as industry communities. This is partly driven by the increasing market demand for indoor location-based services. Due to the limitation of GPS signal strength indoors, nearby anchors with known positions are generally needed for an indoor positioning system. In general, there are two components in indoor positioning systems. One is nearby anchors with the knowledge of their own location information, while the other is a positioning device with the objective of identifying its location by processing wireless signal through nearby anchors. Although the potential needs of indoor navigation services have been already addressed from industry aspects, the ultimate solution in terms of accuracy, reliability, real time, and low cost remains open.

There are several factors that make the design of indoor positioning systems challenging:

- *Cost*: The need to deploy nearby anchors and the development of localization devices to identify objects are costly.
- *Numbers of nearby anchors*: Unlike the traditional navigation GPS system, which uses 31 active satellites in orbit, the indoor environment and space sometimes limit the number of anchors.
- *Complicated indoor environment*: The wireless signal used to measure the distance and angle indoors usually suffers significantly from obstacles, such as walls, objects and/or human beings, which lead to multipath effects.

Due to its wide deployment, we expect WiFi to become a prominent tool for indoor positioning. In this article, we use WiFi access points (APs) with multiple antennas as nearby anchors, while the positioning device could be any mobile platform with WiFi capability such as smartphones or tablets. Since the number of WiFi APs is limited and the system bandwidth is narrow (up to 40 MHz for 802.11n and 160 MHz for 802.11ac), we propose a novel method of sending multiple messages to improve time of arrival (ToA) measurement and angle of arrival (AoA) estimation.

The article is organized as follows. First, we review the conventional indoor localization methods and applications. We then discuss our proposed improved estimates of ToA and AoA, respectively. Next, we describe the application of the proposed mechanisms to WiFi indoor positioning and summarize its performance via simulations. Finally, we conclude our work.

INDOOR LOCALIZATION APPROACHES AND APPLICATIONS

In general, the approaches used in indoor localization can be classified into four categories:

1 Time of arrival
2 Angle of arrival
3 Hybrid ToA/AoA
4 Received signal strength (RSS) and fingerprint

Each of these approaches has its own advantages and limitations.

TIME OF ARRIVAL

Time of arrival is the travel time between a transmitter and a receiver. The distance can be calculated using travel time multiplied by the speed of light. To measure the travel time in the air, this approach usually requires synchronization between transmitters and receivers. In addition, it requires at least three anchors to have the plane-domain (2D) localization as depicted in Fig. 1a and four anchors for 3D localization. The positioning performance is decided by a sig-

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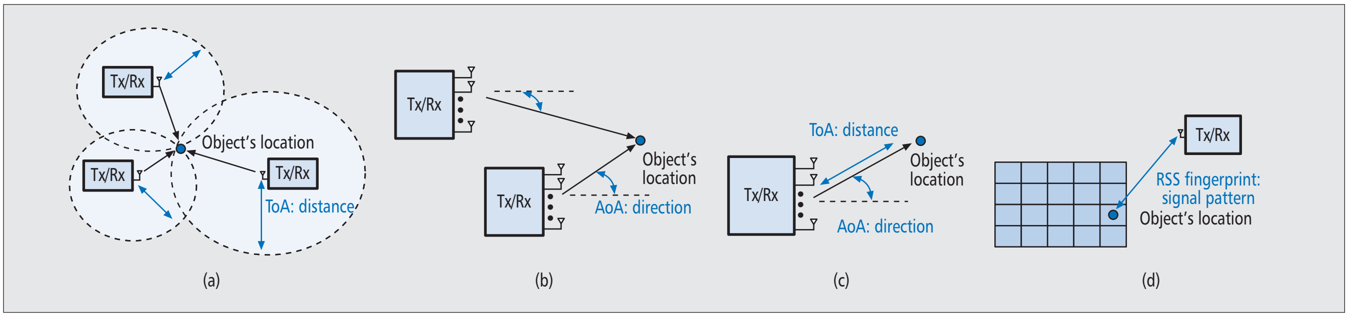

Figure 1. a) Time of arrival approach; b) angle of arrival approach; c) hybrid ToA/AoA approach; d) received signal strength and fingerprint approach.

nal's bandwidth as well as sampling rate [1]. When the arrival wireless signal is sampled in receiver as depicted in Fig. 2, the first sample that captures the arrival signal is not exactly the ToA. In other words, when a signal's bandwidth is not wide enough, the ToA measurement may result in a wide error range of distance. For example, a wireless system with 10 MHz bandwidth as well as sampling rate can only measure the time duration up to 1×10^{-7} s resolution. Therefore, the maximal error in distance is up to $3 \times 10^8 \times 10^{-7} = 30$ m. When the wireless system has 1 GHz bandwidth, the receiver can measure up to 1×10^{-9} s resolution such that the maximal error in distance is lower than 30 CM. Current popular solutions applied to ToA are ultra wideband (UWB) systems [2]. The accuracy a UWB system can achieve is up to 1 cm [3]. However, it requires very wide bandwidth as well as special hardware design to support localization, which results in very high hardware cost.

Angle of Arrival

Angle of arrival measurement is the method that can determine the incoming signal direction from a transmitter on the antenna array. By exploiting and detecting phase difference among antennas [4], the direction of an incoming signal can be calculated. In order to locate the position, this approach requires two anchors with antenna arrays at different places to obtain the object position as depicted in Fig. 1b. However, due to multi-path affection, the AoA in terms of line of sight (LOS) is hard to obtain. An example of a commercial solution applied to AoA is Quuppa's HAIP system where the positioning accuracy can be achieved from 0.5 to 1 m [5]. However, it requires a specific hardware device including 16 array antennas with a transmitter as nearby anchors and a special tag as a positioning device through Bluetooth enhancement of a wireless signal.

Hybrid ToA/AoA Approaches

Due to the complicated indoor environment and limited number of nearby anchors, a hybrid ToA/AoA approach has been introduced [6]. By utilizing the information measured from AoA and ToA, the number of nearby anchors can be reduced. As illustrated in Fig. 1c, it is possible to localize an object using a single nearby anchor. The hybrid approach suffers the same challenge of signal bandwidth as well as the number of antennas. Nevertheless, hybrid systems leverage the benefit from both mechanisms.

Received Signal Strength and Fingerprint

The received signal strength (RSS) and fingerprint is a site-survey approach for positioning [7]. For RSS-alone approaches, the received signal strength ratio reflects the distance information. Through calibration of transmitter power with a corresponding free-space channel model established by measuring distance and power at each point in advance, the coarse distance can be estimated for each anchor node. To further improve location precision, RSS with fingerprint combination is proposed. In general, due to the multi-path effect, each location receives a unique signal through the combination of various rays from different paths. Thus, the signal property, such as frequency response, and signal strength regarding the I/Q channel has its own fingerprint. By associating the signal fingerprint with the target, the anchor can deduce possible location from a pre-measured fingerprint database. This mechanism only requires one anchor node instead of multiple anchors for positioning. In Fig. 1d, the signal fingerprint in each grid is measured in advance. When the object sends the signal toward a nearby anchor (Tx/Rx), the anchor can choose the most similar fingerprint from the database regarding the received signal to do localization. The localization accuracy will depend on not only the size of grid area but also the signal difference among grids. When the difference between signal fingerprints is small, the uncertainty increases.

A commercial solution applying RSS indication (RSSI) alone is Apple's iBeacon technology, and one applying RSS fingerprint-based is Apple's WiFiSLAM. For iBeacon, the location is calculated via a Bluetooth Low Energy system. The coarse distance can be d as immediate, near, and far, three different statuses that refer to within centimeters, a couple of meters, and more than 10 meters, respectively. The WiFiSLAM solution applies a WiFi RSS fingerprint-based mechanism with gyroscope sensor assistance [8] to record each location's fingerprint. WiFiSLAM can achieve up from 1.75 to 2.5 m accuracy. However, it requires a site survey fingerprint in advance. When the environment is dynamic, such as a shopping mall with moving crowd, the performance can degrade dramatically. Moreover, the calculation loading increases exponentially with the numbers of fingerprint points in the database.

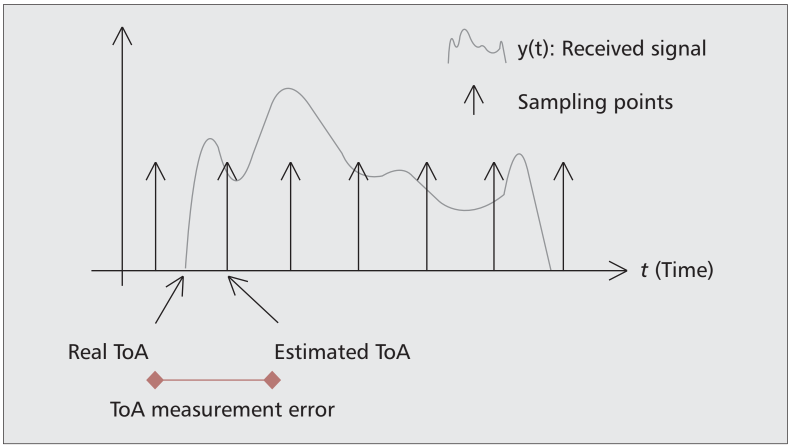

Figure 2. ToA performance vs. transmitter bandwidth.

Minimal Cost for Indoor Localization Infrastructure

Several existing solutions have been investigated through various applications such as UWB, WiFi, and Bluetooth-based applications recently. By considering the cost in terms of deploying anchor nodes as well as the coverage area, the most possible solution is expected in WiFi [9] systems. Unlike a UWB system, WiFi infrastructures have been widely deployed within indoor environments. Comparing with other existing infrastructures such as a Bluetooth-based system, each WiFi anchor node can cover a much wider area than Bluetooth, which costs less anchor nodes. In addition, WiFi has been considered as an important medium for high throughput transmission in indoor environments. In other words, the WiFi hardware capability will follow user desires in terms of high transmission speed by increasing sampling rate with multiple-input multiple-output (MIMO) structure, which can benefit indoor localization performance. The existing work in [10] has shown that a WiFi signal can provide promising performance to overcome indoor multipath, where LOS is possible to detect. By having gyroscope sensors' assistance from mobile phones, the multipath effect can be further mitigated [11]. Therefore, we choose WiFi as a possible solution for low-cost and accurate localization.

Super-Resolution ToA and Performance Improvement

Time of arrival performance is decided by signal bandwidth as well as sampling rate. When the sampling rate is low (narrow bandwidth), the ToA may not be captured precisely. In Fig. 2, the received signal is sampled by the black arrows, while the arrival signal (real ToA) is between two sampling positions, causing the measurement error. The state-of-the-art methods to improve ToA use super-resolution estimation, which is based on subspace decomposition of the autocorrelation matrix and requires the calculation of an inverse matrix with its eigenvectors [12, 13]. Those estimation approaches result in heavy calculation loading, while performance improvement still relies on bandwidth.

In the following, we propose a method that can increase the accuracy of the ToA estimate by sending multiples of the same predefined message to assist estimation. Using the fact that each incoming message is very unlikely sampled at the same place, the collection of multiple received messages in linear time invariant (LTI) channels is able to reconstruct the received signal at higher resolution. We denote the received signal as $y(t)$, while $x(t)$ is the message sent by the sender. Then the received signal can be described as $y(t) = \mathrm{x(t)} \otimes h(t)$, where $h(t)$ is the channel impulse response representing the environment effect, and $\otimes$ is the convolution operation. Given the sampling time period as T_s, the received signal after sampling through an analog-to-digital converter (ADC) can be described as $y_d[n] = y(n \times T_s + \tau) + w[n]$. The $y_d[n]$ and $w[n]$ are the nth sample point in terms of received signal and additive white Gaussian noise (AWGN), while τ is the relative starting point of the sampling position and $\tau \in [0, T_s]$.

If the channel is time invariant and the transmitter sends multiple but equal predefined messages, the received signal after sampling can be described as in Fig. 3. The black, red, and blue arrows represent the sampling of three different arrival messages from the received signal $y(t)$. Since the transmitter has sent the same message multiple times, the receiver will always receive the same signal $y(t)$. One can notice that the sampling positions regarding each incoming signal are not at the same positions. Therefore, the collection of multiple messages with right order can possibly reconstruct the received signal, while we assume that the channel is invariant and the noise is negligible compared to the received signal power level. Taking Fig. 3 as an example, the combination of black, red, and blue samples is able to reconstruct received signal $y(t)$ at higher resolution than using one message alone. Although using multiple messages is able to assist reconstruction of the received signal, how to arrange and make messages in the right order is still not clear. We applied the frequency transform property as in the following to achieve the reconstruction goal.

Time Shift Property

$$\text{If } y(t) \underset{\text{Inverse Frequency Transform}}{\overset{\text{Frequency Transform}}{\rightleftharpoons}} Y(f)$$

$$\text{Then } y(t-\tau) \underset{\text{Inverse Frequency Transform}}{\overset{\text{Frequency Transform}}{\rightleftharpoons}} Y(f)\exp(-j2\pi f\tau)$$

The $\exp(-j2\pi f\tau)$ results in the phase rotation $-2\pi f\tau$ in the I/Q domain. The concept behind the above equation means that the time difference between the same signal received at different times, $y(t)$ and $y(t-\tau)$, can be estimated through the phase shift property in the frequency domain. By repeatedly sending the message from the transmitter, the ith message after sampling in the receiver is described as $y_d^{(i)}[n] = y[n \times T_s + \tau_i]$. If we have the ith and jth messages after sampling as $y_d^{(i)}[n] = y[n \times T_s + \tau_i]$ and $y_d^{(j)}[n] = y[n \times T_s + \tau_j]$, the time difference among these two messages is $\delta\tau = \tau_j - \tau_i$. For fast Fourier transform (FFT) size N, $\delta\tau$ can be calculated by applying the time shift property at subcarrier K as

$$\delta_t = \frac{\angle Y_d^j[K] - \angle Y_d^i[K]}{2\pi \frac{K}{NT_s}} \text{ for } K \in 0,1,2,\ldots,N-1 \quad (1)$$

where $\angle\cdot$ is the phase from the I/Q domain in the receiver and $Y_d^j[K]$ = FFT $\{y_d^j\}$. Due to the cyclic property of discrete time frequency transform, the time difference measuring range is determined by NT_s/K.

Since the receiver can always map the sampling signals to the bit sequence, the resolution of timing difference between two received messages from bit mapping is determined by sampling period T_s and sampling rate. However, further time difference under T_s resolution is hard to obtain. Comparing this with Eq. 1 implies that the time difference can be measured at better resolution beyond the sampling rate limitation. In fact, the measured performance in terms of time difference will depend not only on noise level but also on the choice of subfrequency K. The reason is that different subfrequencies K decide the different measurement ranges such that the same error ratio of phase shift results in different measuring error ranges as well. Therefore, for a predefined message with multiple subfrequencies, we can combine their individual phase shifts to jointly estimate a reliable time difference measurement.

The phase information from the rotation in the frequency domain reflects the time shift between messages. Thus, we can arrange messages with their relative time difference to reconstruct high resolution in terms of received signal. We illustrate this idea using Fig. 3. If the transmitter has sent out three identical messages to the receiver, the received signal at different times may be sampled at slightly different places. These three arrival messages of samples are denoted as $y_d^{(1)}$, $y_d^{(2)}$ and $y_d^{(3)}$. Each message of samples can apply Eq. 1 to allocate the relative place from their time difference. Below, we demonstrate how to estimate ToA in terms of the first message. By placing the other two messages with respect to the first message, we can have high resolution with respect to signal $y(t)$. If the first sample that captures the arrival signal $y(t)$ is from the third message, the ToA can be estimated using the time difference ζ_3 plus the first message timestamp t_q as following $t_q + \zeta_3$. Thus, when the transmitter has sent multiple predefined messages, we can always obtain the ToA through this approach.

One may consider that object's movement could break the linear time invariant (LTI) property. In fact, an indoor object's movement is usually slow, and the wireless channel between a sender and a receiver still remain static over a very short time duration. For example, given a scenario where the object's speed is 20 km/h, the movement in 0.1 ms is 5.6×10^{-4} m. Within this tiny movement, the channel environment between the sender and the receiver can be treated as the same. Therefore, any multiple messages sent within this short time duration are under an LTI channel. Another possible factor that may break the LTI property is a crowded WiFi channel due to the delay caused by channel contention. However, in a WiFi system, there is a sequence of preambles (Physical Layer Convergence Protocol, PLCP, preambles) and multiple OFDM symbols in each packet. Those preambles and orthogonal frequency-division multiplexing (OFDM) symbols can provide multiple subcarriers' messages in each single packet. Therefore, for each received packet, the receiver can estimate the possible arrival time through the sequence of messages. Unless there is no received packet due to heavy collision, the estimated time can be obtained. The more packets the recipient receives under the LTI property, better the performance it can achieve. The receiver can use cyclic redundancy check (CRC) code and channel state information to ensure that the LTI property exists among multiple packets.

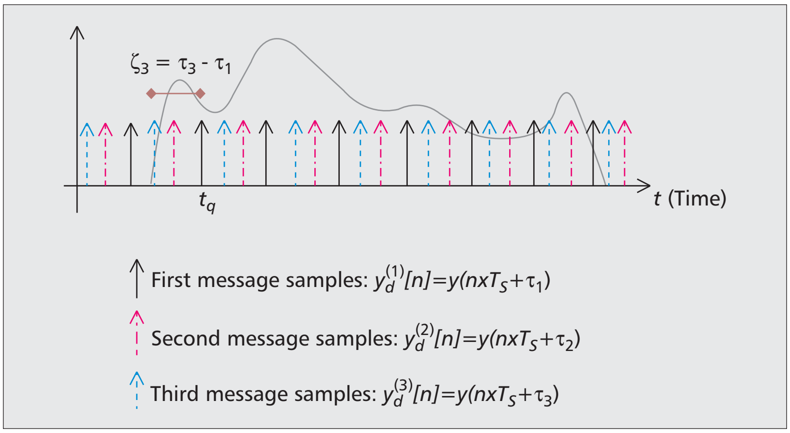

Figure 3. Multiple messages for reconstruction of the received signal.

The signal reconstruction relies on finding the sample of a message that is closest to the arrival signal. We denote this message as *the nearest ToA message* (the blue arrows in Fig. 3), a sample of which is relatively near the arrival signal. In the next section, we show how to utilize *the nearest ToA message* to estimate the AoA information.

AoA Approaches and Constraint Improvement

Generally, AoA is measured using the phase difference of arrival signal among multiple antennas. When incoming messages suffer from the multipath effect, the received signal will suffer from the combination of rays with different AoAs. Traditionally, the approaches to identify the angle with respect to each ray from different paths use multiple signal classification (MUSIC) algorithms [10, 14]. Those techniques are subspace decomposition of the autocorrelation matrix. By finding eigenvectors and an inverse matrix, the algorithms can return angle information with each ray. However, which ray represents the LOS is still not clear, so the LOS AoA information cannot be obtained. Another approach is the joint angle and delay estimation

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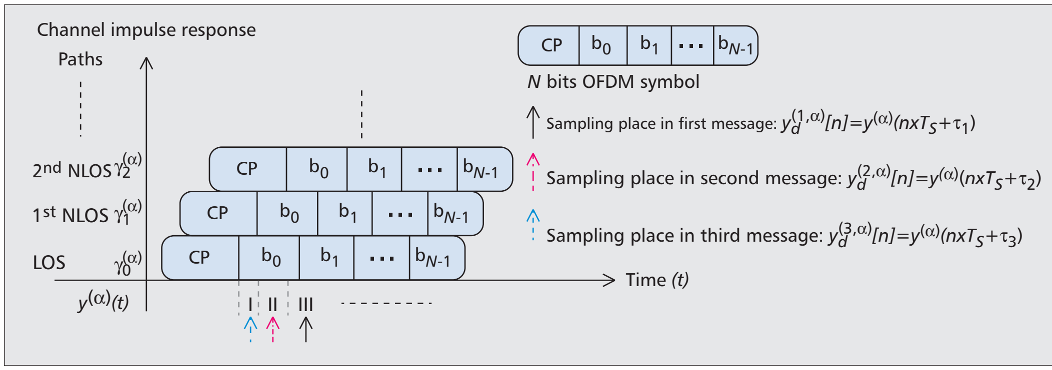

Figure 4. AoA estimation through channel impulse response.

(JADE) method [15]. Although this approach is able to find the AoA with respect to LOS, it requires a many times larger matrix than a MUSIC algorithm for calculation. Moreover, the number of antennas needs to be larger than the number of multipaths. Therefore, the complexity is extremely high.

Since the multipath environment disturbs the AoA measurement, we propose a novel method that can recover from the multipath effect such that AoA can be obtained from the LOS signal. Considering a receiver equipped with N_A antennas, the transmitter sends the predefined message $x(t)$ to the ath antenna of a receiver through wireless multipath channel $h^{(a)}(t) = \gamma_0^{(a)}\delta(t) + \Sigma_{i=1}^{L} \gamma_i^{(a)}\delta(t - \eta_i)$ for $a = 1, 2, \ldots, N_A$. The received signal $y^{(a)}(t)$ can be described as $y^{(a)}(t) = x(t) \otimes h^{(a)}(t)$. We denoted $y_d^{(i,a)}[n]$ as the ith received message after sampling in the ath antenna.

In Fig. 4, the received signal $y^{(a)}(t)$ is the combination of multiple OFDM symbols with each of their delaying times η_i from the multipath effect. The $\gamma_0^{(a)}$ is the channel coefficient of LOS, while $\gamma_1^{(a)}$ is NLOS for $l = 1, 2, \ldots, L$. The complex channel coefficient from LOS among antennas $[\gamma_0^{(1)}, \gamma_0^{(2)}, \ldots, \gamma_0(N_A)]$ indicate the AoA. Hence, if we can obtain channel state information in terms of each ray, we are able to extract the LOS and hence AoA. For OFDM systems, the channel state information can be obtained through channel estimation techniques from pilot assistances of the ith message thus:

$$\hat{h}^{(i,a)}[n] = \mathrm{IFFT}\left\{ H_E\left(\frac{Y_d^{(i,a)}(K)}{X(K)}\right)\right\} \qquad (2)$$

where N is the FFT size, $X(K)$ is the pilot in the K sub-frequency domain, and H_E is the channel estimation approach to estimate the whole frequency response through pilot interpolation. However, the first element in channel impulse response from channel estimation may not be the LOS. The reason is that the sampling positions of a message affect channel estimation. We use Fig. 4 to explain this phenomenon.

When the sampling position is located in zones II and III as $y_d^{(1,a)}$ and $y_d^{(2,a)}$ in Fig. 4, the first ray of channel impulse response as well as LOS will merge and reverse to the last element in $\hat{h}^{(i,a)}[n]$. Thus, it results in $\hat{h}^{(i,a)}[0] \neq \gamma_0^{(a)}$, for $i = 1, 2$. The reason is that the sampling position in zones II and III combines a replica of itself from non-LOS (NLOS), which results in the estimation of channel impulse response not in the right order. In zone I, the sampling position only includes the cyclic prefix (CP) rather than replicas from NLOS, which can be eliminated from channel estimation. Thus, to have LOS in the first element, we can utilize *the nearest ToA message*, the relative sampling position of which is near the arrival time. Hence, by using *the nearest ToA message* in channel estimation, we can obtain channel impulse response with correct order such that $\hat{h}^{(Nearest,a)}[0] = \gamma_0^{(a)}$. Then the LOS angle can be estimated through $\gamma_0^{(j)}$ for $j = 1, 2, \ldots, N_A$ antennas.

The traditional approaches in [10, 15] require a certain number of antennas to overcome the multipath effect. When the amount of multipath increases, more antennas are required to estimate AoA. For example, Quoppa's solution requires 16 antennas with frequency hopping (Bluetooth) to overcome the multipath effect. Our proposed approach does not need to increase the number of antennas. Our minimal requirement for antennas can be only two.

The WiFi-Based Indoor Positioning System

Due to the fact that WiFi technology is widely deployed in indoor environments, we apply our proposed mechanisms to a WiFi system with an access point (AP) with multiple antennas as nearby anchors. The positioning devices could be mobile platforms with WiFi capability such as smartphones and tablets. When there is only one WiFi AP, we apply a hybrid AoA/ToA system to locate the target's positioning. When the number of nearby WiFi APs are two or more, we applied AoA to obtain higher accuracy location. This design can provide accurate positioning service even when the number of nearby anchors is limited.

Since WiFi bandwidth is not as wide as that of UWB, we apply the multiple message approach to assist ToA measurement as well as AoA estimation. In our proposed system, each WiFi AP is equipped with N_A antennas, while the user's mobile phone is equipped with a single antenna only.

DISTANCE MEASUREMENT

In our system, we apply the round-trip time (RTT) approach to obtain distance without requiring time synchronization between transmitters and receivers. In the traditional RTT measuring approach, the transmitter sends the message toward the receiver and records the transmit timestamp. Then, when the receiver responds the message back to the transmitter, the RTT can be calculated from the interval between sending and arrival times. However, this RTT time also includes the receiver processing delay time, and a measurement error occurs. In our scheme, the receiver does not require responding to the message immediately. The transmitter first sends out a burst of messages and records the transmit timestamp of the first message as t_S. Then the receiver uses our proposed ToA approach to measure the arrival time stamp t'_S regarding the first message and allocates the response time started in $t'_S + i \times T_U$, where the T_U is the agreement between transmitter and receiver, and i is the arbitrary number decided by the receiver for allocation convenience. Once the transmitter estimates the first message from receipt with arrival times stamp t_R, the RTT is

$$\mathrm{RTT} = (t_R - t_S) \text{ modulo } T_U$$

One can notice that the ToAs in t'_S and t_R are calculated at each side individually. Hence, the LTI property does not need to hold for the whole RTT estimation process. It only needs to hold for a short time duration while calculating t'_S or t_R. Here, we choose $T_U = N \times T_S$, since each OFDM length is NT_S. Therefore, the maximal measuring distance in a ToA is $NT_S \times C/2$ where C is the speed of light. Take IEEE 802.11n as an example, where bandwidth is 40 MHz and FFT size is 128; the maximal measuring distance under this scenario is up to 480 m. Since WiFi indoor communication distance is usually much less than 480 m, the positioning range from the ToA is quite reliable. By preallocating packet sending in $i \times N \times T_S$, we can reduce the process delay to nearly zero.

ANGLE MEASUREMENT

In our system, the mobile phone sends multiple messages toward the WiFi AP, where the AoA is measured by using the channel estimation technique. The AoA can be obtained by any pair of antennas. When the number of antennas is more than two, the AoA can be jointly estimated for better performance.

LOCALIZATION PROCEDURE

In previous sections we have illustrated how to find out the distance and angle in our system. In the following, we describe the localization procedure:

- **User device**: Requests positioning service of the WiFi AP
- **WiFi AP**: Starts sending requests for RTT measuring
  1. After granting the positioning request, the WiFi AP starts to send burst M messages and records the sending timestamp of first message for later RTT time calculation.
  2. Each message's content is the same and contains multiple subfrequency pilots of an OFDM symbol.
- **User device**: Measures the arrival time and responds with a burst of messages for RTT measurement
  1. The user device reconstructs the received signal by re-ordering the M messages with relative time difference.
  2. The ToA of the first received message can be obtained from the reconstructed signal.
  3. The user device chooses arbitrary i for the sending time $i \times N \times T_S$ to send the burst M messages where each message contains multiple subfrequency pilots.
- **WiFi AP**: Measures the RTT and AoA in terms of user device
  1. The ToA of the first received message can be obtained from the reconstructed signal.
  2. The distance is the RTT multiplied by the light speed divided by 2 where the RTT is the time difference between sending time and received time modulo by $i \times N \times T_S$.
  3. The AoA is measured by using the message nearest the ToA to estimate channel state information.
  4. The WiFi AP returns its own reference location as well as the distance and direction back to the user device.
- **User device**: Uses AoA/ToA to locate its own position and sends requests to other WiFi APs
  1. If the user device only obtains a position from a single WiFi AP, the device calculates its own position by using the WiFi AP reference location with distance and direction angle, as shown in Fig. 1a.
  2. If the user device has positions from more than one WiFi APs, the device only uses AoAs to deduce its own position by combining directions with each WiFi AP, as shown in Fig. 1b.

PERFORMANCE ANALYSIS AND COMPARISONS

We investigate the performance of our proposed system by simulations. We assume sampling rates as well as bandwidth are 20 M/40 MHz, and FFT sizes are 64/128. In addition, we assume each AP has four antennas, while the user device is a smartphone with a single antenna. Among burst messages, the time between them is assumed to be Ts/M where M is the number of burst messages. We consider $M = 10/20$ messages and 16/32 pilots assistance for FFT size 64/128. We demonstrate our system performance through the IEEE 802.11n TGn channel model with different numbers of messages in terms of ToA/AoA.

In Fig. 5, we compare our approaches with a state-of-the-art MUSIC mechanism where the y-axis represents the distance between AP and device in meters, while the x-axis describes signal strength in dB. Since the MUSIC algorithm only

When SNR is low, the noise factor plays an important role to affect phase measurement. Hence, the time shift property, which refers to the time difference between messages, is not precise, and the performance is degraded.

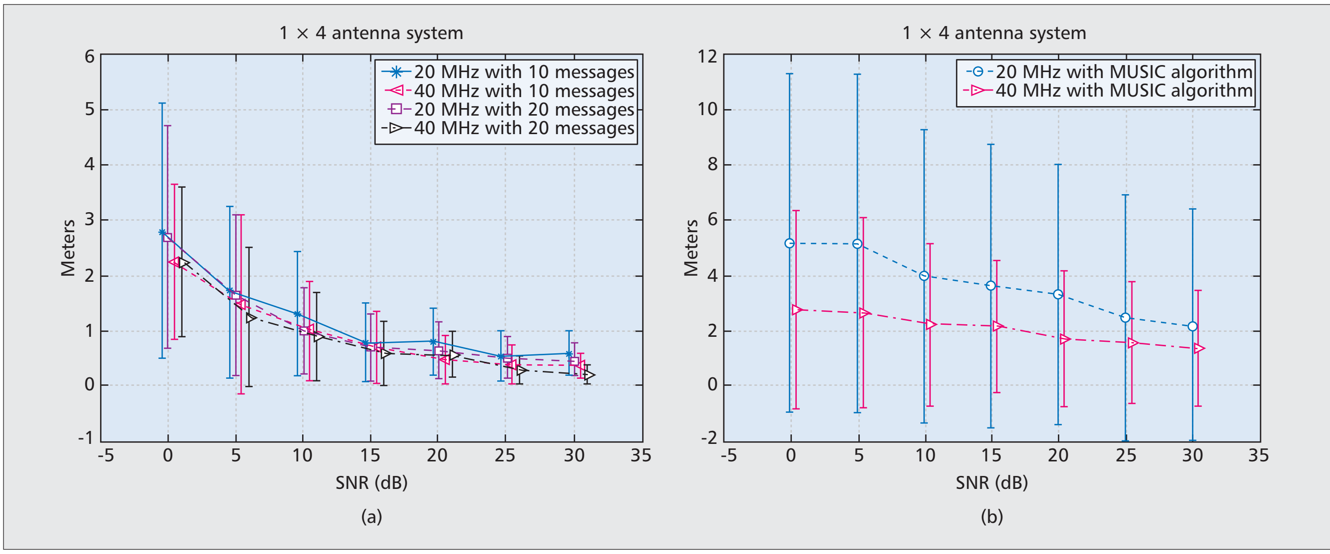

Figure 5. a) Proposed ToA approach performance; b) current state-of-the-art ToA performance (MUSIC algorithm).

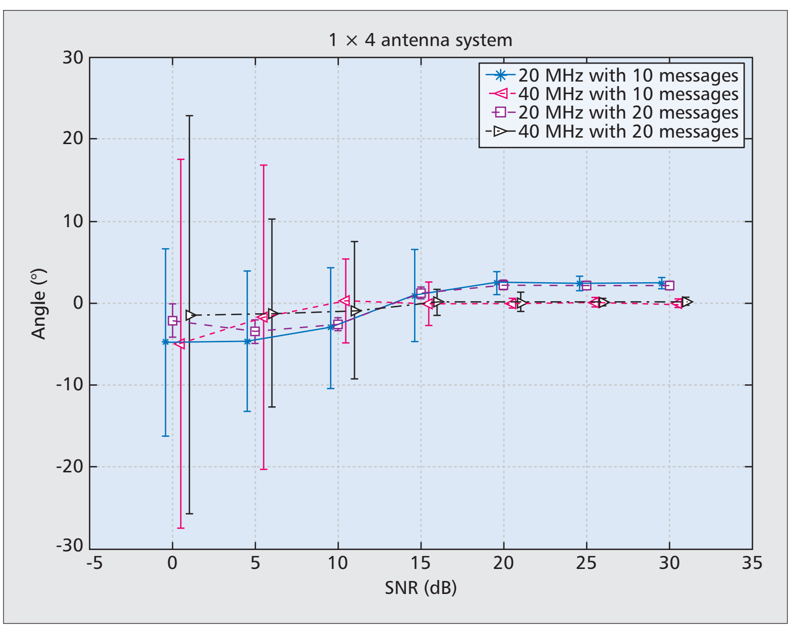

Figure 6. Proposed AoA approach performance.

utilizes one message, the performance is still limited by signal bandwidth. Our proposed solution can provide much better performance through multiple messages. One can notice that 20 messages in 20 MHz bandwidth has similar performance as 10 messages in 40 MHz bandwidth.

For AoA performance in Fig. 6, the angle in the y-axis is calculated by estimating the incoming signal angle with the array of antennas. Figure 6 shows that the AoA performance can be improved by a larger number of messages as well as a wider bandwidth when SNR is high. When SNR is low, the 40 MHz performance is worse than 20 MHz bandwidth. The reason is that FFT size 128 has longer length, and its channel estimation is more sensitive in low SNR, which results in larger errors in AoA. When SNR is higher, the AoA for the message with 32 pilots is much better than the message with 16 pilots.

The positioning error from AoA depends on the distance between the WiFi AP and the mobile device, since the measurement error of angle multiplied by the distance becomes a positioning error. We consider a scenario where the SNR is 20 dB and a WiFi AP's maximal indoor communication distance is 50 m. By utilizing 10 predefined messages, a single WiFi AP can achieve 2.2 and 1 m positioning range for 20 and 40 MHz bandwidth, respectively. When multiple WiFi APs are used, the position performance can reach 2.2 and 0.5 m, respectively. When SNR is low, the noise factor plays an important role to affect phase measurement. Hence, the **time shift property**, which refers to the time difference between messages, is not precise, and the performance is degraded. Nevertheless, our proposed mechanism achieves superior performance under current WiFi AP hardware conditions.

Conclusion

We illustrate different mechanisms and their applications used in indoor localization in terms of cost and complexity. The conventional ToA/AoA approaches to overcome bandwidth limits and numbers of multipaths are introduced and discussed. We show that our proposed approach can improve ToA resolution compared to the super-resolution method under limited signal bandwidth without heavy calculation loading. Moreover, our proposed AoA approach through multiple message assistance can reduce the need for multiple antennas. We demonstrate the performance by applying the mechanism to a WiFi-based indoor positioning system where it can support localization with just a single WiFi AP. When the number of nearby WiFi APs is two or more, the position accuracy can improve further by AoA joint positioning. Finally, simulation showed that our proposed approach provides superior performance without changing hardware settings in a practical WiFi AP setting.

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