A New Statistical Time of Arrival Ranging Algorithm

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Abstract

The accuracy of 60 GHz millimeter wave based indoor localization is mainly determined by the accuracy of the measurements employed. These measurements can be affected by the propagation environment, such as multipath fading due to a Non Line of Sight (NLOS) channel. To improve the localization accuracy, a new ranging algorithm for 60 GHz wireless systems is proposed based on Time of Arrival (TOA) measurements. This algorithm is compared with previously developed approaches such as the Mean Value Algorithm (MVA) and the High Probability Algorithm (HPA) using the IEEE 802.15.3c indoor channel model. Performance results are presented which show that the proposed algorithm can provide improved accuracy, particularly in poor channel conditions.

Keywords: 60 GHz,Time of Arrival (TOA), Non-Line-of-Sight (NLOS), multipath fading

1. Introduction

The demand for high data rate wireless communications with low latency has increased dramatically in recent years. Unfortunately, due to spectrum limitations and transmit power regulations, current short-range wireless communication technologies cannot achieve Gigabit per second (Gbps) data rates. Fortunately, wireless communications in the 60 GHz millimeter wave (mm-wave) band has become viable for Gbps wireless communication networks [1-4] due to the availability of several GHz of license-free spectrum, up to 10 W maximum transmit power, no interference from other systems, and the development of low-cost Complementary Metal-Oxide Semiconductor (CMOS) devices. The Federal Communications Commission (FCC) permits communications in the 60 GHz unlicensed band at an Effective Isotropic Radiated Power (EIRP) of up to 40 dBm, which is many times greater than other short-range wireless communication technologies. In China, this limit is 44 dBm [5]. Although the Path Loss (PL) is high at 60 GHz, the received power can still be significant. Impulse radio communication technologies have been proposed for this frequency band because it can be effective in separating the multipath signals at the receiver. This is because short pulses are employed for communications with a duration (typically under 100 picoseconds), which is far less than the multipath propagation delay. These signals can also provide the fine multipath resolution required for high precision ranging and localization [6].

The accuracy of 60 GHz mm-wave-based indoor localization is mainly determined by the accuracy of the ranging measurements employed. These measurements can be affected by the propagation environment, for example, Non-Line-Of-Sight (NLOS) propagation, multipath fading, and inter-symbol interference [7-11]. In [12], an algorithm was presented which uses the ranging results to directly calculate the location, but this often leads to poor accuracy because of the presence of outliers. In [13], the Mean Value

Algorithm (MVA) is proposed which uses the mean value of several consecutive Time of Arrival (TOA) measurements to calculate the position. Although this provides improved error performance compared to the algorithm in [12], large errors can still occur because of the randomness of the error distribution. The High Probability Algorithm (HPA) was proposed in [14]. This algorithm uses the highest probability values from several consecutive TOA measurements. Compared with the approaches in [12] and [13], the error is much smaller in an Ultra-Wide Band (UWB) wireless system. However, in a 60 GHz system, results show that the HPA will not significantly reduce the error with TOA measurements in many circumstances *e.g.*, IEEE802.15.3c channel CM2.2, and the error can even be greater compared with the MVA in some cases *e.g.*, IEEE802.15.3c channel CM2.4. Thus a more accurate method, *i.e.*, the Statistical Algorithm (SA), is proposed here to overcome the drawbacks of existing methods. Results are presented which show that this TOA estimation algorithm provides better values for localization which improves the precision compared to previous algorithms.

The remainder of this paper is organized as follows. In Section II, TOA estimation over an IEEE802.15.3c channel is introduced. In Section III, the proposed statistical algorithm is discussed. Some simulation results and a performance comparison are given in Section IV. Finally, Section V concludes the paper.

2. TOA Estimation over An IEEE802.15.3C Channel

Currently, there are two important standards that have been developed for 60 GHz communications systems, IEEE 802.15.3c and IEEE 802.11ad [15-16]. In this paper, the channel models in IEEE 802.15. 3c standard are used because it is specifically designed for Wireless Personal Area Networks (WPAN) and thus encompasses typical indoor environments. Further, these are the most widely employed models for 60 GHz systems. The IEEE 802.15.3c standard was the first developed for high data rate short-range wireless systems. The physical layer was designed to support the transmission of data within a few meters at a minimum data rate of 2 Gbps. These models have been developed for communications in the frequency band 57 to 66 GHz in indoor residential, indoor office and library environments (with differences largely due to the LOS and NLOS characteristics) [17-21]. The focus here is on the indoor residential and indoor office channels as these are the most typical environments.

In this paper, a Pulse Position Modulation Time Hopping (PPM-TH) 60 GHz signal is employed for ranging purposes. The propagation delay $\hat{\tau}$, between the transmitter and receiver is estimated for use in localization.

2.1. The Transmitter

The PPM-TH 60 GHz signals have a very short duration (typically 100 picoseconds or less), and can be expressed as

$$s(t) = \sum_{-\infty}^{+\infty} p\left(t - jT_s - C_j T_c - a_j \varepsilon\right) \tag{1}$$

where T_s is the symbol time. The Time Hopping (TH) code represented by C is a pseudorandom integer-valued sequence which is unique for each user to limit multiple access interference, and T_c is the chip time. The PPM time shift is ε so that if a_j is 1, the signal is shifted in time by ε, while if a_j is 0, there is no shift. Many pulse shapes have been proposed for 60 GHz systems. In this paper a Gaussian pulse is employed which is multiplied by the carrier signal to give [22]

$$p(t) = \frac{\sqrt{2}}{\alpha} \exp\left(-2\pi \frac{t^2}{\alpha^2}\right) \cos\left(2\pi f_c t\right) \tag{2}$$

where α is the shape factor, and f_c is the carrier frequency which here is $f_c = 60$ GHz.. A smaller shape factor results in a shorter duration pulse and a larger bandwidth.

2.2. Propagation Channel

Because of multipath propagation, the received signal can be expressed as

$$r_1(t) = \sum_{i=1}^{L} \beta_i p(t - \tau_i) + n(t) \tag{3}$$

where L is the number of received multipath components with β_i and τ_i denoting the amplitude and delay of the nth path, respectively, and $n(t)$ is Additive White Gaussian Noise (AWGN) with zero mean and two-sided power spectral density $N_0/2$ [23].

The path loss (PL) is defined as the ratio of the received signal power to the transmitted signal power and so is a key component for performance analysis. Unlike narrow-band systems, the PL for a wide-band system such as a 60 GHz mm-wave system is both distance and frequency dependent. In order to simplify the analysis, it is assumed that the PL frequency dependence is negligible [24]. The PL then depends on the propagation distance only and the channel (IEEE802.15.3c), and so can be expressed as

$$PL(d)[\text{dB}] = PL_0 + 10 \cdot n \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma[\text{dB}]; \quad d \geq d_0 \tag{4}$$

where d_0 and d denote the reference distance and distance between the transmitter and receiver, respectively. The PL exponent n for mm-wave indoor environments ranges from 1.2-2.0 for LOS channels and from 1.97-10 for NLOS channels. Due to wave guide and reverberation effects, and the power levels with multipath aggregation, n can be smaller than 2 [25]. $X_\sigma[\text{dB}]$ is a Gaussian random variable with mean zero and variance σ_s, with units in dB which represents the shadowing [26]. Table 1 summarizes the values of n, PL_0, and σ_s for different environments.

Table 1. Values of *n*, *PL*$_0$, σ_s for Different IEEE802.15.3c Channel Environments

IEEE802.15.3c Channel Environment		n	PL_0	σ_s
indoor residential (LOS)	CM1	1.53	75.1	1.5
indoor residential (NLOS)	CM2	2.44	86.0	6.2
indoor office (LOS)	CM3	1.16	84.6	5.4
indoor office (NLOS)	CM4	3.74	56.1	8.6

2.3. Received Signal

The received signal can be written as

$$r_2(t) = s(t) * h(t) + n(t) \tag{5}$$

where $s(t)$ is the transmitted signal, and $h(t)$ is the channel impulse response which can be expressed as

$$h(t,\theta) = \sum_{k=1}^{K}\sum_{l=1}^{L_k} \mu_{kl}\delta(t - T_k - \tau_{kl})\delta(\theta - \theta_k - \omega_{kl}) \tag{6}$$

where $\delta(.)$ is the dirac delta function, K is the number of clusters, L_k is the number of rays in the kth cluster, and μ_{kl}, τ_{kl} and ω_{kl} denote the complex amplitude, delay and azimuth of the kth ray of the lth cluster, respectively. Similarly, T_k and θ_k represent the delay and mean Angle of Arrival (AOA) of the kth cluster.

2.4. Propagation Delay Estimation

The goal is to obtain an unbiased estimate of the TOA $\hat{\tau}$ from the received signal $r(t)$. This signal is correlated with a reference template $s(t - \tau)$ to obtain an estimate the propagation delay corresponding to the position of the correlation peak given by

$$\hat{\tau} = \arg\max_{\tau} \int r(t)s(t - \tau)dt \tag{7}$$

The distance between the transmitter and receiver can then be estimated as $d = c \times \hat{\tau}$, where c is the speed of light.

3. The Statistical Algorithm

TOA location performance is highly dependent on the accuracy of the range measurements which may be degraded by factors such as multipath propagation and NLOS signals, particularly in an indoor environment. In this section, a statistical algorithm is presented to obtain an accurate estimate of d for use in localization algorithms. Let the transmitted signal power be 40 dBm, the sampling frequency be $f_s = 10^{11}$ Hz, and the signal to noise ratio (SNR) be 5 dB. Figure 1 shows the distribution of d obtained via simulation using the IEEE802.15.3c CM2.1 channel model with a range $d = 5$ m. this shows that more than 860 of the 1000 estimated ranges are distributed near the actual range of 5 m. This indicates that if the values with a high probability of being near the actual range can be identified, the accuracy of the range measurements will be improved significantly. The statistical algorithm has been developed to achieve this goal and is given in Figure 2. The variable denoted as *digit* is used to determine the precision of the distance estimate. When *digit* = 1, the input data is rounded to the nearest integer. When *digit* < 1, the input data is rounded to the corresponding power of 10. For example, if $a = 6.5482$, when *digit* = 1, round(a) = 7, and when $digit = 10^{-2} = .01$, round(a)=6.55. Our extensive simulation results indicate that when digit < .01, the error in the TOA measurements will not be significantly reduced. Therefore the algorithm stops when digit < .01.
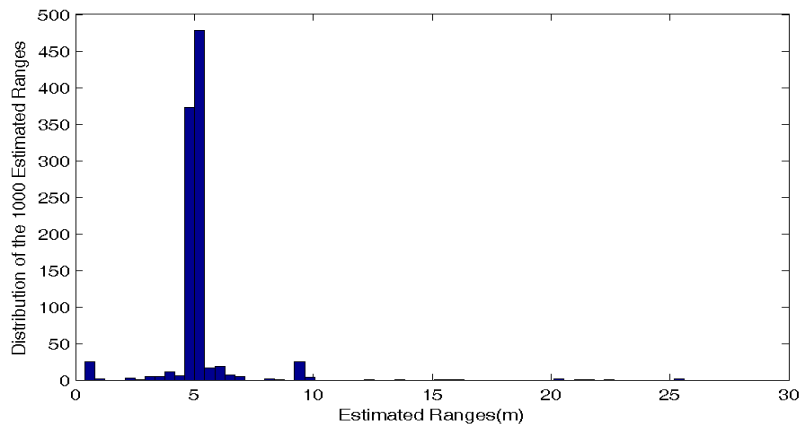
Figure 1. Distribution of the Estimated Ranges

For example, the IEEE802.15.3c residential environment channel CM2.1 was employed to obtain 10 measurements with the same channel parameters as used for Figure 1. The algorithm proceeds as follows.

1) The parameters i and *digit* are initialized to 0 and 1, respectively. The measured ranges are input to the data array X_0 = [6.0888, 6.1068, 6.1278, 1.5349, 5.9988, 6.0288, 6.0618, 10.5497, 6.0648, 5.9988].

2) The input data array X_0 is rounded to [6, 6, 6, 2, 6, 6, 6, 10, 6, 6], so the maximum probability is $P_{maxi} = 0.8$ for $V_{maxi} = 6$ and the second largest probability is $P_{smaxi} = 0.1$ for $V_{smaxi} = 2$ or 10.

3) Comparing P_{maxi} with P_{smaxi}, as $P_{maxi} >= 0.25$ and $P_{smaxi} < 0.25$, the elements in X_i equal to V_{maxi} are stored in array A_0 so that A_0 = [6.0888, 6.1068, 6.1278, 5.9988, 6.0288, 6.0618, 6.0648, 5.9988].

4) Set $i = 1$, *digit* $= 10^{-1} = .01$, and let $X_1 = A_0$. The elements in X_1 are rounded to give [6.1, 6.1, 6.1, 6.0, 6.0, 6.1, 6.1, 6.0], so the maximum probability is $P_{maxi} = 0.625$ for $V_{maxi} = 6.1$ and the second largest probability is $P_{smaxi} = 0.375$ for $V_{smaxi} = 6.0$.

5) Comparing P_{maxi} with P_{smaxi}, as $P_{smaxi} >= 0.25$, the elements in X_1 that were rounded to min(V_{maxi}, V_{smaxi},) are stored in array A_1 so that A_1 = [5.9988, 6.0288, 5.9988].

6) Set $i = 2$, *digit* $= 10^{-2} = 0.01$, and let $X_2 = A_1$. The elements in X_2 are rounded to give [6.00, 6.03, 6.00], so the maximum probability is $P_{maxi} = 0.67$ for $V_{maxi} = 6.00$ and the second largest probability is $P_{smaxi} = 0.33$ for $V_{smaxi} = 6.03$.

7) Comparing P_{maxi} with P_{smaxi}, as $P_{smaxi} > 0.25$, the elements in X_2 are rounded to min(V_{maxi} V_{smaxi}) are stored in array A_2 so that A_2 = [5.9988, 5.9988].

8) The mean of the elements in A_2 is 5.9988, which is near the actual range of 6. On the other hand, the mean value algorithm and high probability algorithm give 6.0555 and 6.0588 respectively, which is further from the actual range. The error with the mean value algorithm is only slightly lower than the error with the high probability algorithm.
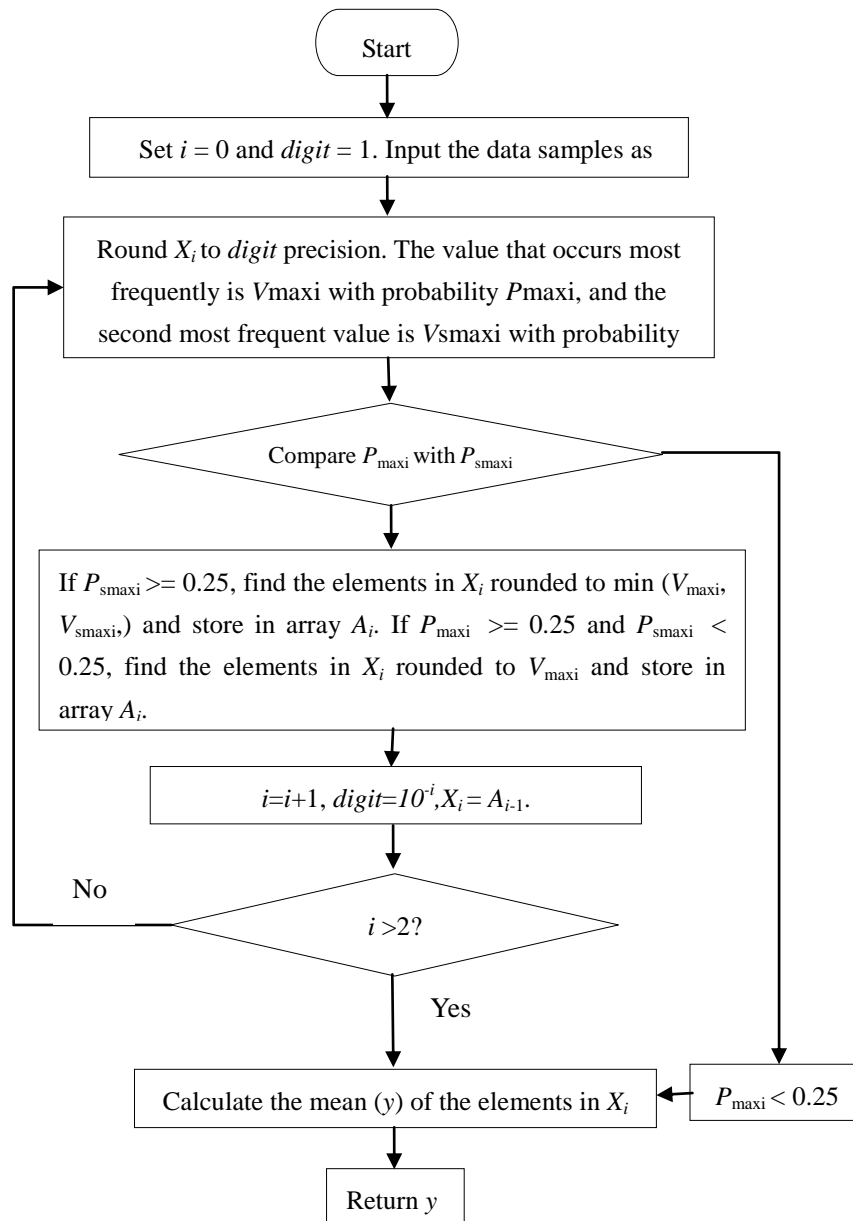
Figure 2. Flow Chart of the Proposed Statistical Algorithm

4. Ranging Accuracy

In the IEEE.802.15.3c standard, the indoor residential NLOS channel, i.e. CM2, has four versions denoted CM2.1, CM2.2, CM2.3, and CM2.4. In order to verify the effectiveness of the SA in different environments, results were obtained for all four versions. As before, the transmitted signal power is 40 dBm, the sampling frequency is $f_s = 10^{11}$ Hz, and the Signal to Noise Ratio (SNR) is 5 dB. Groups of 10 TOA measurements were obtained using the proposed SA algorithm as well as the MVA and HPA. The error is $|y\text{-}d|$, where y is the SA, MVA or HPA ranging result. The ranging performance with these channels is shown in Figure 3 (CM2.1), Figure 4 (CM2.2), Figure 5 (CM2.3), and Figure 6 (CM2.4). In all cases the accuracy of the SA algorithm is the best, while the accuracy of the MVA is much worse in many cases. The error with the HPA is

approximately 0.04 m, while the error with the SA is near 0. With the CM2.4 channel and a range of 6 to 9 m, HPA (which has the highest complexity), provides no improvement in ranging accuracy compared to the MVA. In some cases, the HPA accuracy is less than that with the MVA, for example the CM2.4 channel with a range of 10 m and 12 m.
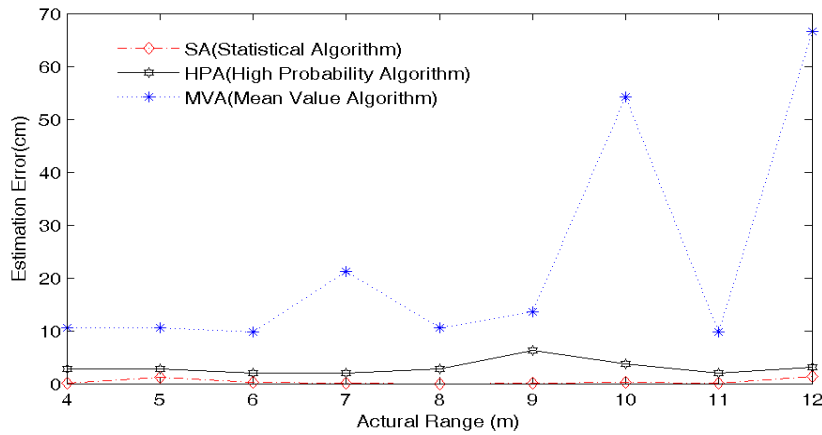

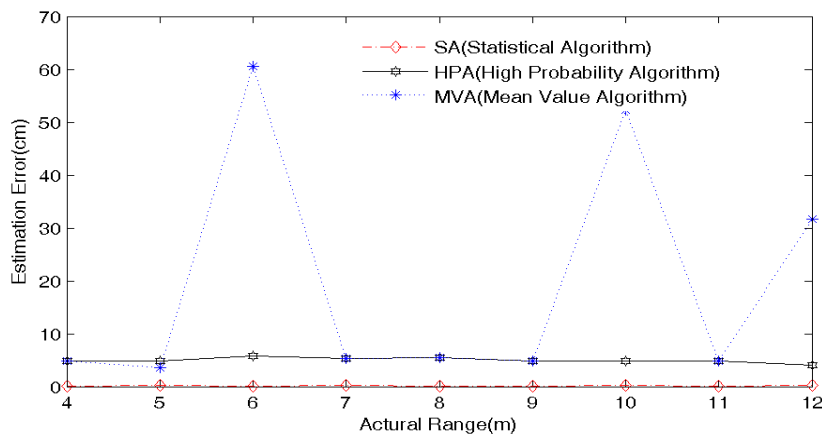**Figure 3. Ranging Error with Three Algorithms in Channel CM2.1**

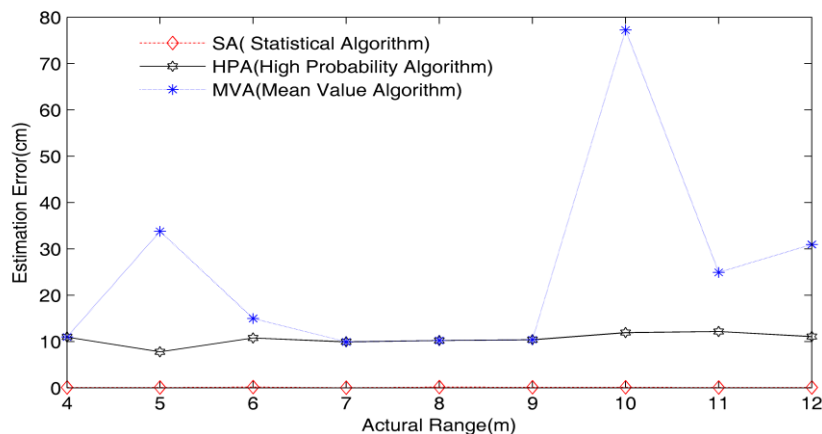
Figure 4. Ranging Error with Three Algorithms in Channel CM2.2

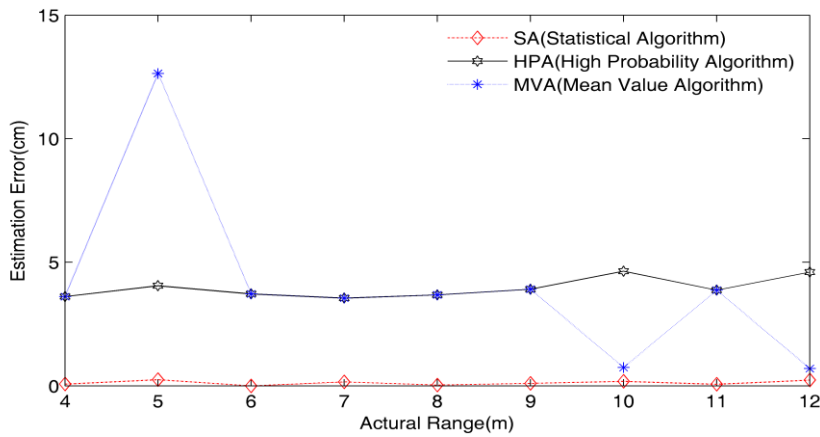**Figure 5. Ranging Error with Three Algorithms in Channel CM2.3**

Figure 6. Ranging Error with Three Algorithms in Channel CM2.4

In order to further verify the performance of SA algorithm for ranging in the 60 GHz wireless networks, results were obtained for the indoor office NLOS channel, *i.e.*, CM4. In the IEEE.802.15.3c standard, there are two versions of this channel, CM4.1 and CM4.2. The ranging performance with channel CM4.1 is shown in Figure 7, and for channel CM4.2 in Figure 8. The accuracy of the SA is still the best, and the performance of the MVA and HPA degrade rapidly, although MVA is better than HPA.
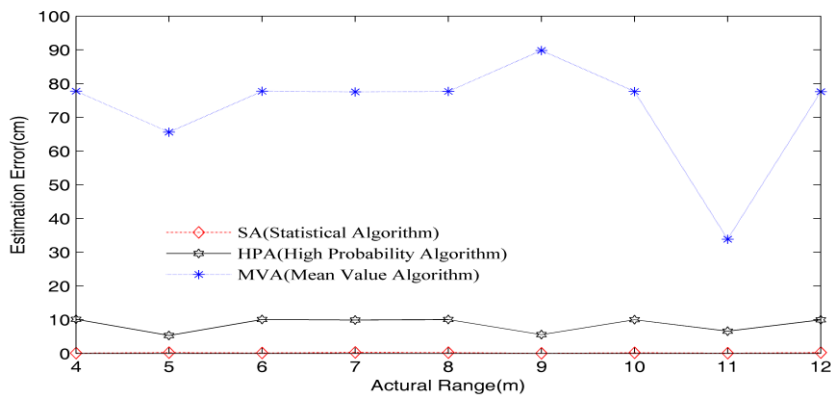

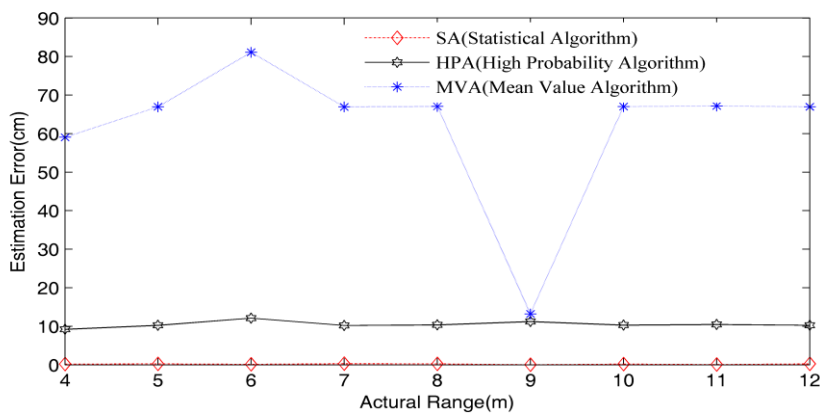**Figure 7. Ranging Error with Three Algorithms in Channel CM4.1**

Figure 8. Ranging Error with Three Algorithms in Channel CM4.2

5. Conclusion

The accuracy of ranging measurements for localization can be affected by the propagation environment, for example, Non Line of Sight (NLOS) signals, multipath fading, and inter-symbol interference. To improve localization performance in such cases, a new Statistical Algorithm (SA) was developed for 60 GHz mm-wave-based indoor ranging using Time of Arrival (TOA) measurements. The effectiveness of the SA in different environments was verified via extensive simulations using the IEEE 802.15.3c channel models. The High Probability Algorithm (HPA) and Mean Value Algorithm (MVA) were compared with the proposed SA with the IEEE 802.15.3c indoor residential CM2 channel model and indoor office CM4 channel model. These results show that the SA provides the lowest error (best ranging accuracy), compared to the other algorithms.

Acknowledgments

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