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RSSI ve ToA Tabanlı Mesafe Tahminlerini Kullanarak Kablosuz Sensör Düğümlerinin Bağıl Lokalizasyonu

Relative Localization of Wireless Sensor Nodes by Using the RSSI and ToA Based Distance Estimations

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Öz

Kablosuz sensör ağları, Wi-Fi, Bluetooth, ZigBee ve WiMAX gibi kablosuz altyapıları kullanarak bağlanan birçok sensör düğümünden oluşur. Sensör düğümlerinin göreli veya mutlak konumlarının belirlenmesi birçok uygulama için önem taşımaktadır. Sunulan çalışmamızda, tercih edilen kablosuz iletişim altyapısının Alınan Sinyal Gücü Göstergesi (RSSI) ve Varış Zamanı (ToA) metriklerinden elde edilen sonuçları birleştirerek sensör nodlarının konumunu daha yüksek başarımlı tahmin etmek için geliştirilmiş bir yöntem sunulmaktadır. Konum analizinin sonuçları ölçümlere ve nodlar arasındaki mesafelerin karşılaştırmasına dayanarak sunulmaktadır. Önerilen yöntem RSSI ya da ToA verilerine dayalı kestirim sonuçlarını düğümler arasındaki mesafeye göre tercih etmektedir, kısa mesafelerde RSSI uzak mesafelerde ise ToA tercih edilmektedir. Sonuçlar, bileşik yöntemin tahmin hatalarını azalttığını ve her iki yöntemden de daha iyi performans sergilediğini göstermektedir.

Anahtar Kelimeler: *Kablosuz Sensör Ağları, Konumlama, RSSI, TOA*

Abstract

Wireless sensor networks (WSNs) consist of multiple sensor nodes connected via wireless infrastructures, such as Wi-Fi, Bluetooth, ZigBee, and WiMAX. Determining the relative or absolute positions of these nodes is crucial for various applications. In this study, an improved method for estimating the position of WSN nodes is presented that combines the estimation results of the Received Signal Strength Indicator (RSSI) and Time of Arrival (ToA) metrics from the preferred wireless communication infrastructure. Results of the position estimation are compared based on both measurements and distance between the nodes. The proposed method uses position estimations based on both RSSI and ToA metrics, but the result of a single method is favored depending on the distance between nodes, with RSSI being superior for short distances and ToA for farther distances. The results demonstrate that the proposed combined method reduce estimate errors and perform better than either method alone.

Keywords: *Wireless Sensor Networks, Localization, RSSI, TOA*

1. Introduction

With the advancing technology and the growing demand, everything is becoming connected over wireless infrastructures. This connectivity also covers sensor applications by connecting sensors over a wireless network. A wireless sensor network (WSN) is a network of many nodes equipped with one or more sensors, capable of computation, communication, and sensing [1]. Advancements in embedded electronics led to smaller and low power electronic components and modules and as a result WSN based applications have spread to several areas in recent years. A sensor node is composed of a processor, a memory, a sensor or sensors, and a wireless communication module as presented in Fig. 1.

The WSN nodes might be fixed or mobile depending on the application. In outdoor applications such as seismic monitoring, WSN nodes are fixed and their position change is evaluated to measure the movement of tectonic plates [2]. Another example for a fixed sensor node is the ecosystem monitoring, where the position of the node is predefined to the system [3].

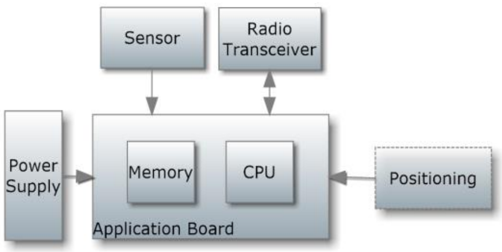

Figure 1. Structure of a sensor node.

For cases employing mobile nodes, estimating the position of nodes is frequently required depending on the application. In outdoor applications, space-based radio-navigation systems or base station signals of mobile networks can be used for estimating the position of the node [4]. However, GPS satellites cannot cover indoor locations, and signals from base stations located outside become unpredictable. Therefore, especially for indoor applications, an application-specific localization gives better results in many cases.

Many researchers have studied estimating the locations of sensor nodes in indoor environments. These methods are generally classified as range-based or range-free algorithms [5]. A range-based algorithm is based on the distance estimates between the nodes, while a range-free algorithms uses connectivity between the nodes and static wireless landmarks [6]. The precise estimation of the distance between each sensor node is critical for the range-based methods; however, the accuracy of the distance estimation depends on the environment as well as the RF infrastructure and the distance between the WSNs. For improper conditions distance estimation between the nodes using a specific metric could lead to insufficient distance estimates which will result in faulty location estimates [7].

In this paper, an improved localization method is proposed for sensor nodes based on the standard metrics of a wireless infrastructure. Two of the standard metrics, the Received Signal Strength Indicator (RSSI) and the Time of Arrival (ToA), are used to estimate the distance between the nodes, and the resulting distance is determined as a result of one of these methods based on the estimated distance. Trilateration relative to the position of the reference node is then applied to estimate the location of each sensor node. The positions of the nodes are therefore based on a relative coordinate system where the reference node is placed in the origin. The major contribution of this paper is to define a proper limit point between the RSSI and ToA methods based on properties of the hardware and validate this limit definition by experimental results.

The rest of the paper is organized as follows: A brief survey of the literature is presented in Section 2, while in section 3; an overview of theoretical background and the methodology is introduced. In Section 4, we present both the measurement results and comparison of them and conclude these results in Section 5.

2 Related Work

Several localization methods have been presented in the literature. Trilateration, which is also preferred in our work is also employed in vaious studies. Neuwinger et al. propose a range-free self-organizing localization algorithm for mobile sensor nodes. [8]. In this work, the position of a mobile node is assumed to be stable during localization. The node to be localized acquires three coordinate data and then evaluates its coordinate by trilateration. An off-the-shelf localization integrated circuit called nanoLOC is employed and the results show that the error increases with the increasing distance up to 27.5 m. [8]. A trilateration algorithm for indoor localization based on RSSI data has been proposed by Yang et.al. [9]. The authors preprocessed the measurement data by a Gaussian filter to reduce noise, and then least-squares curve fitting (LSCF) is employed to estimate the power transmitted and the path loss. These values are then used as input data for the trilateration algorithm which builds an error function based on estimated distances and mobile anchors. A final Bayesian filtering based denoising step is also presented in the paper to decrease the influence of the process noise. The results of the proposed method are promising.

Fingerprint data-based research results are also presented in various papers. Yu, Yang, and Li propose a method based on adaptive model recognition and construction based on the RSSI fingerprint characteristics to improve the accuracy and robustness of the localization [10]. Results presented in the paper show that the proposed method performs better than the conventional methods due for the non-Gaussian RSSI distributions. A fingerprint based positioning method for both indoor and outdoor localization based on mobile communication systems is presented by Zou et. al. [11]. Instead of employing a classical radiomap they use a traffic regulation radiomap, which uses road directions instead of locations of the stations and enables tracking the movement direction of the user. They use the generated radiomap as offline information and implement this information into the mobile application as fingerprint data. As the user travels between clusters, this data is employed. According to the test results evaluated by using mobile phones, 5 m. positioning accuracy for pedestrian speeds is achieved, however, the method is focused on the outdoor applications and indoor performance is rather weak. Mosleh, Abed, and Abbas present a case study based on the partitioning of the test area into multiple zones [12]. Each zone is constructed from a number of walls, doors, and windows and allocated specific propagation parameters used to estimate the target positions with a significantly reduced error. Presented results confirm that the locations are estimated with an average error of 2.8 m. for one zone and 0.192 m. for four zones while 2.4 m. for one zone and 0.217 m. for four zones for the RSS based estimation. Ahmed et al. proposed a comparison of trilateration and centroid positioning positioning approaches based on RSSI values. [13]. According to the presented simulation results, trilateration appears to be a better positioning system than centroid.

The presented work in this paper is a range based method which is also presented by several researchers. An adaptive range-based localization (ARBL) based on trilateration and reference node selection algorithm is proposed by Luomala and Hakala [14]. The distance estimation uses RSSI values. Authors introduce a metric to evaluate the geometry of reference triangle (GRT) while the GRT values are computed from a previously selected reference node set. The selection criteria for the reference nodes is based on ranging error and localization geometry. Authors claim that localization performance is improved significantly when compared to standard RSS based localization techniques. A range-based method, considering the tendency of the RSSI values acquired from the node beacons, is presented by Sahu et al. [15]. They prefer the acronym "Dual RSSI Trend based Localization" (DuRT) for their method and apply polynomial models based on trajectories to locate the maximum RSSI value to be used and therefore minimize the error due to uncertain distance estimations. The method is claimed to be favorable in dynamic domains and performs better by increasing the number of beacons. They present three different variants for their method, namely DuRT-M1, DuRT-M2 and DuRT-All and compare the results. Mitilineos has reported experimental results for three different range-based indoor localization schemes [16]. The first method they propose is based on wireless nodes called *Cricket*s. Each *Cricket* propagates an RF pulse as a beacon signal. The distance between two nodes is estimated using the propagation time of the beacon to another. Using trilateration, nodes are located based on their relative distances from one another. The second method presented in the paper is based on evaluating the ToA and the Direction of Arrival (DoA) information tags transmitting ultra-wideband (UWB) signals and UWB receivers. The position of the UWB receiver is estimated by employing trilateration using the distance estimates based on the ToA information. DoA information is used to select the correct distance estimate. The third approach works on a ZigBee network and is called *WAX* localization. First RSSI measurements are performed and an RSSI fingerprint database is created for the environment. Then RSSI measurements of the nodes are acquired and used to evaluate the distance between nodes. Trilateration is used as the last step to estimate the position of each node. It is claimed that, *WAX* method is the most accurate one [16]. Garcia et al. proposed two range-based methods for a Wi Fi based WSN that is installed on the surface. They used fixed access points for trilateration base localization and a heuristic training measurement system [17]. Their results imply that, the trilateration based system gives more precise results, while, for environments with various reflection losses, heuristic approach performs better.

There are also hybrid techniques that employ more than one method or metric to improve the results. Zhai, Yang, and Cui present a hybrid method that uses the time difference of arrival (TDoA) and the frequency difference of arrival (FDoA) [18]. The authors propose a convex boundary projection algorithm to estimate the location of the propagating source. Their results are close to the Cramer-Rao lower bound (CRLB), although it uses less resources and is more efficient. A hybrid localization algorithm for wireless sensor networks is presented by Liu et. al. [19]. Authors propose a hybrid indoor positioning algorithm employing approximate point in triangle (APIT) and distance vector-hop (DV-HOP) algorithms. The results show that the localization performance improved 78% with respect to APIT and %49 with respect to DV-HOP. Karmy, ElSayed, and Zekry propose a hybrid RSSI / TDOA localization system for Visible Light Communication (VLC) technology using LEDs [20]. The location of the target is estimated using RSSI only at places with received power is above predetermined threshold level and TDOA elsewhere. The results imply that the error rate is reduced from 7.34 cm (RSSI alone) to 5.81 cm. Another hybrid approach is proposed by Tripathy and Khilar to enhance localization accuracy employing both Distance Vector Hop and a weighted amorphous algorithms [21]. First distance is estimated using the weighted amorphous algorithm and then refined using the Vector Hop approach. The Hop value is evaluated by estimating the minimum number of relays between the beacon and the target node. Authors claim improved localization results in means of Mean Absolute Error, Root Mean Square Error, and Mean Square Error.

Beyond these approaches, there are hybrid studies that are using RSSI and ToA as reference metrics. In the work presented by Zhang and friends, authors propose a least squares support vector regression based three-dimensional localization algorithm based on RSSI and TOA information is proposed [22]. A single anchor node is determined first, and WSN nodes are localized accordingly by using RSSI ranging in the short distance and TOA ranging in the longer distance. In the work presented MATLAB based simulation results are presented which as more accurated than LSSVR-based or RSSI-TOA-based localization methods. Zaldi and friends propose a method based on selection of the localization technique as RSSI or ToA based on the anchors [23]. The RSSI method is used for small distances and the ToA method is preferred for greater distances and call their method as Combined Advantages of ToA-RSSI (CA ToA-RSSI). MATLAB based simulation results presented in the paper show that the positioning accuracy is improved compared with the RSSI and ToA based ranging methods. In the work presented by Günay and Çavdar a wireless sensors localization method for the elements of a fleet by using RSSI, TOA and TDOA (Time Difference of Arrival) methods is presented [24]. MATLAB based simulations presented in the work show that RSSI performs better in close distances even with several mobile nodes are located however ToA and TDoA perform better for larger distances. The proposed algorithm also detects if the movement is linear or curved and determines which methods to be involved. For a linear movement ToA and RSSI combination is preferred however for curved movement ToA, TDoA and RSSI is preferred. The hybrid methods presented previously involve RSSI and ToA as presented in our method and the approach is also very similar as in the close distances and ToA is preferred in larger distances, however none of the previously mentioned methods are based on measurement parameters, but they are based on simulation results. In our work several measurement results are presented.

3. Methodology

In this work, WSNs are built using a Wi-Fi module with a Realtek RTL8723BU chip as communication hardware between the nodes. This module is capable of working both as an access point and as a client, depending on the configuration. To obtain proper communication metrics from the hardware, each node is configured as an access point or as a client for distinct measurements.

3.1 Received Signal Strength Indicator-Based Distance Estimation

RSSI is a relative power indicator metric, which needs some processing to evaluate the absolute power received by the module. Integrated circuit manufacturers usually share the corresponding received power in dBm with the RSSI value that varies between 0 and 255. While '0' corresponds to the strongest received signal level [25].

After evaluating the absolute power received, we start the range estimation process. The received power is directly proportional to the transmitted power and several types of losses. The power transmitted by module is provided by the hardware vendors [25]. Losses can occur for a number of reasons, including mismatched cables and connectors, mismatches in impedances, polarization errors, as well as propagation errors. In this work antennas used are identical on both ends and matched to the feed network, therefore polarization and impedance mismatch losses are negligible. Since the antennas are connected directly to the board, cable and connector losses can also be neglected. Consequently, the only cause of the loss is limited with the propagation loss.

The propagation loss depends on the distance and the environmental effects. For the operating conditions and the environmental parameters presented in our previous study [26] the two ray propagation model performed better when compared to other models, therefore it was preferred for this study.

Two-Ray Ground Reflection Model includes a directly propagating electromagnetic wave from the transmitter to the receiver and a reflected wave from the closest surface as presented in Fig 2 [27], where the reflecting surface is the ground, which is also similar to our work. The propagation loss for the two-ray ground reflection model is presented in Equation (1)

$$L_{tr} = 20log\left(\frac{d^2}{h_t h_r}\right) \quad (1)$$

where d is the distance between the WSN nodes, and h_t and h_r denote the transmitter and receiver heights, respectively.

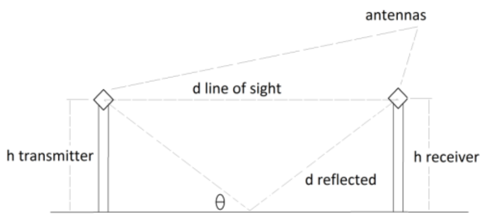

Figure 2. The line of sight between the antennas and the reflection rays.

In order to estimate the distance between two sensor nodes we need to place the heights and the evaluated loss value from the RSSI metric into equation (2).

3.2 Time of Arrival Based Range Estimation

In the work presented by Rezar and Ricciato an analysis of source positioning methods using time-of-arrival (ToA) measurements is presented [28]. They define a sphere with the reference user located in the center called the "convex hull" and present their analysis results as inside or outside this sphere. According to their results Time of Departure information is very effective outside the sphere while minor inside.

According to the IEEE 802.11v standard [29], WLAN packets are time stamped to achieve time synchronization as presented in Fig. 3. This time stamp also includes a ToA parameter transmitted to the two ends of the communication link. The resolution of the time stamp according to the standard is 10 nano seconds. Time of Departure (ToD) represents the departing time of the WLAN packet from the transmitter. Therefore, a good synchronization between the receiver and the transmitter is essential for correct ToA information.

Category	Action	Dialog Token	Follow Up Dialog Token	ToD	ToA	Max. TOD Error	Max. TOA Error

Figure 3 Timing measurement frame format defined in IEEE 802.11v [29]

The message exchange scheme for time synchronization between transmitter and receiver is presented in Fig. 4 [29]. The transmitter for this case is the wireless access point (AP) and transmits the first frame TM1 to measure the propagation time of the wave to the receiver node. The ToD of TM1 is acquired by the receiver at time t2. The receiver node sends acknowledgement message at t3 after successfully receiving of TM1. For the transmitter to synchronize with the receiver node, it is required that the timestamps t1 and t4 should be available at the receiver. Therefore, TM2 is sent by AP which carries t1 and t4 as TOD and TOA. The receiver node sends an acknowledgement after receiving this message and uses the timestamps to evaluate its ToA value using Equation (2):

$$t_{ToA} = \frac{(t_2 - t_1) + (t_4 - t_3)}{2} \quad (2)$$

The ToA method uses the t_{ToA} value to evaluate the distance between the sensor node and the AP, by multiplying it by the speed of propagation, which is equal to the light speed for wireless signals. Therefore, the distance is estimated using the following simple formula;

$$d = c \times t_{ToA} \qquad (3)$$

where c is the speed of light, t_{ToA} is the ToA metric and d is the distance between two nodes.

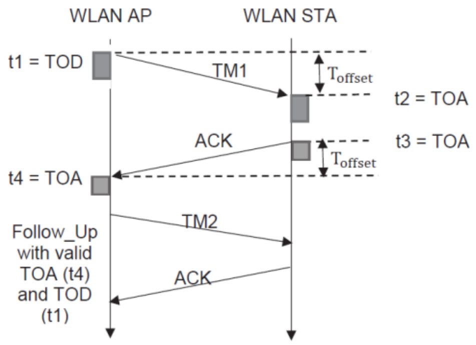

Figure 4 Message exchange for synchronization in IEEE 802.11v [29]

3.3 Relative Positioning Algorithm

The relative localization takes the first node, which is denoted 'a', as the reference node. For positioning four sensor nodes, the reference node is located at the origin of the relative two-dimensional Cartesian coordinate system, as presented in Figure 5. Since we have a distance estimate between nodes 'a' and 'b' called L_{ab}, node 'b' can be placed at any point in the distance estimate. For simplicity and without losing generality, we place it on the 'y' axis, at position (0, L_{ab}) as can be observed in Figure 5. By locating node 'b', y axis and consequently x axis of our relative coordinate system is formed since the coordinate system is a two dimensional one.

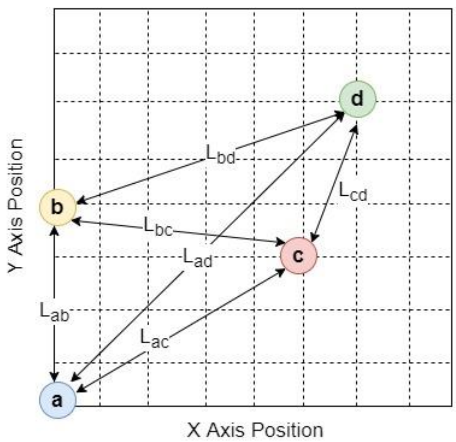

Figure 5. Relative coordinate system with nodes *'a', 'b', 'c'* and *'d'*.

Based on the distance estimates L_{ac} and L_{bc}, we can place node 'c' on the recently formed relative coordinate system. This time we have two possible locations due to the intersection of the circles of the trilateration method presented in the preceding section. For node 'c' presented in Fig. 9, there are two possible locations that are symmetrical with respect to the y axis of the coordinate system. We prefer the estimate of node 'c' corresponding to the positive x values and move on to node 'd'. According to the trilateration, since we have three nodes with estimated distances, namely L_{ad}, L_{bd} and L_{cd}, for node 'd', we only have a single possible estimated location for is which is presented also in Fig. 9. For further number of nodes the procedure is similar to node 'd' and have a single possible position on the relative coordinate system formed by the first three nodes. A detailed description of the relative positioning algorithm is presented in [26] and in the flowchart presented in Fig. 6.

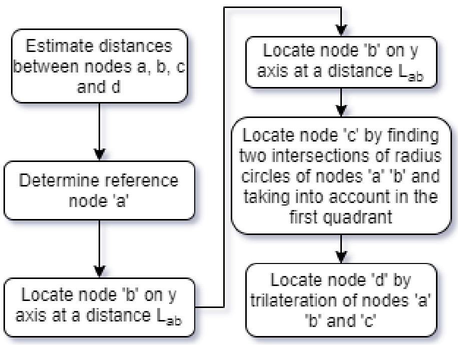

Figure 6. Relative localization algorithm flowchart

3.4 Combined Localization Method

Both the ToA and RSSI methods suffer from uncertainty of the measured range. The RSSI value is affected not only by the distance and the ground reflected ray, but can also be affected by surrounding obstacles, antenna orientation, noise and interference. Therefore, the range estimated using the acquired RSSI value corresponds to a range interval rather than a definite distance. The same parameters as well as the resolution of the time stamp also affect the ToA parameter and create uncertainty for the estimated distance [30].

The environment does not affect RSSI and ToA metrics in the same way. In the short range with a direct line of sight (LoS), RSSI metric is very reliable since the reflected waves from surrounding obstacles, walls etc. rather traveled a larger distance and attenuated much more than direct waves and ground-reflected waves [7]. However, with increasing distance, reflected waves are much more effective and result in fading of the signal at some distances, as presented in Fig 7 [31]. This fading effect results in the estimation of a closer distance as a farther distance and creates uncertainty.

Time-of-flight-based trilateration is affected by delay spread of the impinging signal as well as error created by the resolution of the time stamp. The delay spread is caused by multipath reflections, and the received signal for a single pulse looks like a series of pulses. A good example of delay spread from the work of Varela and Sanchez is presented in Fig. 8. As can be seen in the figure the first pulse which is caused by the line of sight signal or a signal with least number of reflections is followed by signals with smaller amplitude and delayed approximately 5 nanoseconds [32]. The delay spread results with an inter signal interference (ISI) and affects the received signal quality. However, for positioning algorithms, only the first received signal is used to estimate the shortest distance between the transmitter and the receiver. Therefore, the effect of delay spread is minimal for trilateration-based positioning.

As mentioned previously, time-of-arrival-based trilateration relies on the relation between distance and the time it takes a radio signal to travel that distance. This presents a more reliable way to estimate the distance between the transmitter and the receiver, since it is not affected by the attenuation of the signal due to interference of multipath signals. However, the major limitation for this method is the resolution of the time stamp of the ToA metric [33]. Most commercial devices offer a nanosecond time stamp resolution depending on the manufacturer and technology implemented. Since electromagnetic waves traveling at free space travel in the speed of light, 1 nanosecond corresponds to propagation of the wave for 0.33 meters which also defines the resolution of the distance estimation[34]. The estimated distance can be in an interval of 0.33 m. for any sequential time stamp values. Since this estimation error is fixed, the ratio of the error is less for further distances; however, for closer distances our rate of error becomes significant.

Another factor affecting the estimation error of for ToA based estimation is the clock rate of the wireless module. Even if the time stamps promise a resolution of 0.33 m., time stamp information can be acquired with the triggering of the clock signal edge, which brings another limitation for closer distances. The ToA information will not be acquired if the clock of the receiving module does not trigger in time, therefore sime ToA data will be outdated or misinforming in close distances. **The highest operating frequency of the preferred wireless module is given as 52 MHz and an electromagnetic wave can propagate 5,76 m. in this time interval which determines the border between the RSSI and ToA estimations.** For distances closer than this limit RSSI based estimation will be preferred and for further distances ToA based estimations will be taken into consideration. It is important to note that this border is determined by the characteristic clock frequency of the wireless module and can vary accordingly.

4 Experimental Results and Discussion

The experimental results are evaluated using 4 wireless sensor nodes placed in three different preset positions. For each measurement, one of the WSNs is programmed as the host, the other WSNs are programmed as clients, and the RSSI and ToA metrics are acquired for this preset condition. For example, for the first measurement of the first scenario, node ‘a’ is the host, and RSSI and ToA metrics are acquired from node ‘a’ for nodes ‘b’, ‘c’ and ‘d’. In the next step, node ‘b’ is the host and the same metrics for nodes ‘a’, ‘c’ and ‘d’ this time.

4.1 Wireless Sensor Nodes

Four single-board computer (Raspberry Pi 2 B+) based WSNs are built and implemented as presented in Figure 7. A Wi Fi/Bluetooth module (Realtek RTL8723BU) with an external antenna and a sensor board are implemented on the single-board computer. Sensor data is acquired via SPI interface of the Raspberry Pi.

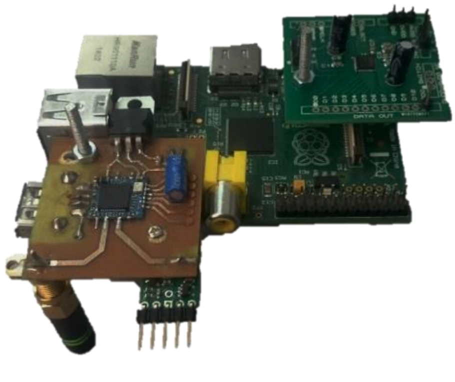

Figure 7 Wireless Sensor Node Implementation

The automatic gain control (AGC) function of wireless modules is used to save battery by adjusting the gain on the transmitter and receiver parts of the module. This results in faulty measurements, since it cannot be controlled manually. Therefore, during measurements, the AGC of the Wi-Fi module is disabled to acquire a correct signal strength value. Output power of the module is given as 17 dBm for the preferred IEEE802.11b standard and receiving sensitivity is given as –85 dBm [35].

4.2 Testbed

According to the methodology presented above four WSNs are located on a testbed according to three different configurations namely; near range, mid-range and far-range. The locations of the nodes with respect to these configurations are presented in Table 1 and Fig. 7. The location of node 'a' is the reference and always at the origin, so it is not presented in the table. Based on the predefined positions of each node, the distance between nodes is calculated. A photograph of the testbed can be observed in Figure 8. The testbed for these experiments is free of obstacles and walls and the nodes are close to the ground, therefore, there is only a ground reflection as a multipath interference.

Table 1. Node coordinates for three different cases

Range	Nodes	X coordinate (m.)	Y coordinate (m.)
Mid	b	0	2,5
	c	2,2	5,7
	d	4,8	4,2
Near	b	0	2,2
	c	1,5	3
	d	3	2,2
Far	b	0	8
	c	6	9
	d	10	8

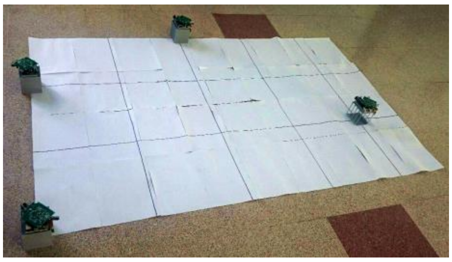

Figure 8. Photograph of the testbed for mid-range configuration

4.3 Measurement Results

Both RSSI and ToA metrics were recorded 20 times for each measurement on the SBC automatically. The following subsections present average results for RSSI and ToA based distance estimations based on these measurements.

4.3.1 RSSI Measurements

For four nodes, there exists six distance values in between the nodes, that are L_{ab}, L_{ac}, L_{bc}, L_{ad}, L_{bd}, and L_{cd}. Two Ray ground reflection model presented in section 3.1.1 is used to estimate these distances between the nodes and trilateration based localization, which is presented in section 3.3.2, is used to estimate the position of each node according to the RSSI measurements.

Localization results for the mid-range, near-range and far-range measurements are presented in Table 2.

Table 2. Estimated Node Coordinations for Three Different Cases with RSSI metric

Range	Nodes	X		Y	
		Actual	Estimated	Actual	Estimated
Mid	b	0	0	2,5	2,6
	c	2,2	2,3	5,7	6,2
	d	4,8	4,7	4,2	4,8
Near	b	0	0	2,2	2,5
	c	1,5	2,5	3	2,4
	d	3	2,8	2,2	3
Far	b	0	0	8	4,2
	c	6	5,2	9	8
	d	10	6,9	8	6,9

4.3.2 ToA Measurements

Time of Arrival measurements are also acquired with the RSSI values at the testbed setup at same node positions. Table 3 presents the results for the ToA based position estimations. It can be observed that, especially for the far range setup, ToA-based positioning results are superior to the RSSI based ones.

In Table 4 error performance of both methods are compared for all three range setups. The error is evaluated as the difference between the actual and estimated locations. As can be seen in the table for the near range, the error performance of both metrics is similar to each other. However, for the mid-range distances, performance of the RSSI based localization is approximately 30% better than the ToA based one. For the far range ToA based results have significantly less error when compared to mid and far ranges, however RSSI based results got worse. For the far range, ToA performs six times better than the RSSI based methodology.

Table 3. Estimated Node coordinates for three different cases with ToA metric

Range	Nodes	X		Y	
		Actual	Estimated	Actual	Estimated
Mid	b	0	0	2,5	2,55
	c	2,2	3	5,7	5,8
	d	4,8	4,2	4,2	4,95
Near	b	0	0	2,2	2,05
	c	1,5	2,1	3	2,1
	d	3	2,2	2,2	3
Far	b	0	0	8	8,1
	c	6	6,1	9	8,5
	d	10	9,5	8	8,1

As presented in Table 4 neither of the methods performs well in the whole range. Especially for the RSSI based method, the far range estimation error rate is as high as 150%, which means a very wrong estimation. In the combined localization method, position of a WSN is estimated using both methods but the result of a single method is preferred for each range. If the location of a WSN is in the first 5 m. of the reference node result of the RSSI Method is preferred while for the ranges beyond 5,73 m. (see section 3.4 for determination of this value) result of the ToA based method is preferred. The decision is made according to an initial estimation based on the ToA method, and the decision for the following estimations preceding the estimate is used to decide which method is preferred.

Due to the combined methodology, the overall error percentage is reduced to 10% as can be seen in Table 5. For the experimental results presented, mid-range ‘c’ and ‘d’ are beyond 5 m., therefore estimation result of the ToA based method is preferred for these nodes. The combined method performs better than both RSSI- and ToA-based methods alone.

The lower bound on the estimation of the variance of any unbiased estimator is set by the Cramer-Rao lower bound (CRLB).In order to evaluate our results derive the CRLB of localization using location information and the propagation model introduced in the preceeding sections. The CRLB for node “d” is evaluated according to the method introduced by Sun and friends [36]. As can be observed Fig.9 the average of the estimate error approaches the corresponding CRLB for node “d” especially after switching the algorithm. CRLB highly depends on the number of nodes used to estimate the position therefore; it is possible that experimentations with higher number of nodes will result in closer results to the CRLB.

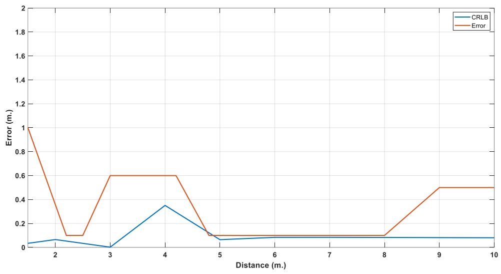

Figure 9. CRLB analysis of the proposed method.

Comparison of the proposed method with aforementioned methods in the introduction section is presented in Table 6. Since other methods are not tested in all regions defined in our study only possible results are presented. All the corresponding ranges are close to the defined ranges in our study. Closest work to be compared is the work presented by Yang and Li and our results are better in the near range, both results are close in the mid range, however the compared work is better than our proposed work. In the mid range our result out performs the work presented by Casacuberta and Ramirez and slightly better than the work presented by Neuwinger. Nevertheless it must be mentioned that none of these works use neither the same module nor RF sensitivity and output power values are comparable with our work.

Table 4 Comparison table for both methods. All units are in meters

	Near Range (0-2 m.)				Mid Range (2-5 m)				Far Range (5-10 m)				Overall Average
Nodes	b	c	d	Avg.	b	c	d	Avg.	b	c	d	Avg.	
RSSI Error	0,14	0,63	0,54	0,75	0,30	1,15	0,8	0,44	3,75	1,68	3,33	2,92	
RSSI %	6%	10%	8%	8%	12%	19%	13%	14%	150%	27%	52%	77%	33%
ToA Error	0,07	0,81	0,91	0,78	0,15	1,09	1,09	0,60	0,20	0,55	0,84	0,53	
ToA %	3%	13%	14%	10%	6%	18%	17%	14%	8%	9%	13%	10%	11%

Table 5 Error performance of the combined method. All units are in meters

	Near Range (0-2 m.)				Mid Range (2-5 m)				Far Range (5-10 m)				Overall Average
Nodes	b	c	d	Avg.	b	c	d	Avg.	b	c	d	Avg.	
Combined	0,14	0,63	0,54	0,75	0,15	1,09	0,8	0,44	0,2	0,55	0,84	0,53	
Combined%	6%	10%	8%	8%	6%	18%	13%	12%	8%	9%	3%	10%	10%

Table 6 Comparison of error performance of the proposed method with the referenced methods

Method	**Near Range**	**Mid Range**	**Far Range**	**Farther**
Proposed	%8	%12	%10	-
Casacuberta and Ramirez	-	%30	-	%8,3
Liu et. al (2016)	-	-	%10	-
Cricket	-	-	-	%3
Ubisense	-	-	-	%12
Wax	-	-	-	%1
Mosleh (2021)	-	-	%3	-
Neuwinger (2009)	-	%14	-	-
Yang (2019)	%16	%10	%4.5	-

5 Conclusions

In this work, indoor localization results for three different range setups of four wireless sensor nodes are presented based on RSSI and ToA based distance estimations between the nodes and a combined method is proposed based on these results. Measurements showed that, when the nodes are distributed with an average distance of 2,5 meters (near region), error performance of both techniques is similar; however, for the midrange where the distance is around 5 meters, performance of the RSSI based localization is considerably better than the ToA based method. For the far range we can see that the ToA based method is much more superior (nearly six times better performance) to the RSSI based localization, even if same trilateration and relative localization technique is employed for both methods. Therefore, combining the results of these methods based on the distance between the reference node gives better performance, as presented in Table 3. The comparison table presented in the previous section shows that most studies do not cover all the regions defined in this study, however results of our work present comparable performance in all three regions. This combination method depends on the measurement environment, as a future work developing an adaptation algorithm is planned to determine the parameters depending on the fingerprint data of the environment, so that the method will be applicable to any environment where we do have the fingerprint data for a specified frequency.

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References

[1] I. F. Akyildiz, T. Melodia, and K. R. Chowdury, "Wireless multimedia sensor networks: A survey," *Wirel. Commun. IEEE*, 2007, doi: 10.1109/MWC.2007.4407225.

[2] S. Scheer, R. Mendes Jr., T. F. Campestrini, and M. C. Garrido, "Fundamental Test of Seismic Information and Building Damage Data Gathering System using OSHW with Wireless Sensor Network," *Sixth Annu. Int. Conf. Comput. Civ. Build. Eng.*, 2014, doi: 10.1061/9780784413616.053.

[3] A. Mainwaring, D. Culler, J. Polastre, R. Szewczyk, and J. Anderson, "Wireless sensor networks for habitat monitoring," in *Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications - WSNA '02*, 2002, doi: 10.1145/570738.570751.

[4] J. Yick, B. Mukherjee, and D. Ghosal, "Wireless sensor network survey," *Comput. Networks*, 2008, doi: 10.1016/j.comnet.2008.04.002.

[5] G. Han, J. Jiang, C. Zhang, T. Q. Duong, M. Guizani, and G. K. Karagiannidis, "A Survey on Mobile Anchor Node Assisted Localization in Wireless Sensor Networks," *IEEE Communications Surveys and Tutorials*. 2016, doi: 10.1109/COMST.2016.2544751.

[6] A. PAL, "Localization Algorithms in Wireless Sensor Networks: Current Approaches and Future Challenges," *Netw. Protoc. Algorithms*, 2010, doi: 10.5296/npa.v2i1.279.

[7] T. Türkoral, Ö. Tamer, S. Yetiş, E. İnanç, L. Çetin, "Short Range Indoor Distance Estimation by Using RSSI Metric" . IU-Journal of Electrical & Electronics Engineering Vol 17 No:114 3295-3302.

[8] B. Neuwinger, U. Witkowski, and U. Rückert, "Ad-hoc communication and localization system for mobile robots," in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2009, doi: 10.1007/978-3-642-03983-6_26.

[9] B. Yang, L. Guo, R. Guo, M. Zhao, and T. Zhao, "A Novel Trilateration Algorithm for RSSI-Based Indoor Localization," *IEEE Sens. J.*, vol. 20, no. 14, pp. 8164–8172, 2020, doi: 10.1109/JSEN.2020.2980966.

[10] Y. Yu, L. Yang, and H. Li, "An adaptive model recognition and construction method for RSSI fingerprint-based localization," *Meas. Sci. Technol.*, vol. 30, no. 12, 2019, doi: 10.1088/1361-6501/ab285f.

[11] D. Zou *et al.*, "Design of a Practical WSN Based Fingerprint Localization System," *Mob. Networks Appl.*, 2019, doi: 10.1007/s11036-019-01298-4.

[12] M. F. Mosleh, F. A. Abed, Z. A. Hamza, Improving Indoor Localization System Using a Partitioning Technique Based on RSS and ToA. Journal of Techniques, vol. 3, no. 1, pp. 47–54, 2021 https://doi.org/10.51173/jt.v3i1.278

[13] A. Ahmed, A. Talpur, N. Bohra, and S. Khan, "Performance Analysis of RSSI based Localization in WSNs," *1st Int. Conf. Comput. Sci. Technol. 10-12 April 2019 (INCCST'19), MUET Jamshoro*, no. April, pp. 10–12, 2019.

[14] J. Luomala and I. Hakala, "Adaptive range-based localization algorithm based on trilateration and reference node selection for outdoor wireless sensor networks," *Comput. Networks*, vol. 210, p. 108865, Jun. 2022, doi: 10.1016/J.COMNET.2022.108865.

[15] P. K. Sahu, E. H. Wu, J. & Sahoo, . DuRT: Dual RSSI trend based localization for wireless sensor networks. IEEE Sensors Journal, 2013, Vol 13, no:8, 3115-3123. [6502185]. https://doi.org/10.1109/JSEN.2013.2257731

[16] S. Mitilineos, D. M. Kyriazanos, O. E. Segou, J. N. Goufas, S. Thomopoulos, "Indoor Localisation with Wireless Sensor Networks," Progress In Electromagnetics Research, Vol. 109, 441-474, 2010. doi:10.2528/PIER10062801

[17] M. Garcia, J. Tomas, F. Boronat, and J. Lloret, "The development of two systems for indoor wireless sensors self-location," *Ad-Hoc Sens. Wirel. Networks*, 2009.

[18] X. Zhai, J. Yang, and L. Cui, "Wireless network localization via alternating projections with TDOA and FDOA measurements," *Ad-Hoc Sens. Wirel. Networks*, 2017.

[19] C. Liu, S. Liu, W. Zhang, and D. Zhao, "The Performance Evaluation of Hybrid Localization Algorithm in Wireless Sensor Networks," *Mob. Networks Appl.*, vol. 21, no. 6, pp. 994–1001, 2016, doi: 10.1007/s11036-016-0737-1.

[20] M. Karmy, S. Elsayed, and A. Zekry, "Performance enhancement of an indoor localization system based on visible light communication using rssi/tdoa hybrid technique," *J. Commun.*, vol. 15, no. 5, pp. 379–389, 2020, doi: 10.12720/jcm.15.5.379-389.

[21] P. Tripathy and P. M. Khilar, "An ensemble approach for improving localization accuracy in wireless sensor network," *Comput. Networks*, p. 109427, Oct. 2022, doi: 10.1016/J.COMNET.2022.109427.

[22] L. Zhang, Z. Wang, Z. Kuang, and H. Yang, "Three-dimensional localization algorithm for WSN nodes based on RSSI-TOA and LSSVR method," *Proc. - 2019 11th Int. Conf. Meas. Technol. Mechatronics Autom. ICMTMA 2019*, pp. 498–503, Apr. 2019, doi: 10.1109/ICMTMA.2019.00116.

[23] M. Zaidi *et al.*, "Cooperative Scheme ToA-RSSI and Variable Anchor Positions for Sensors Localization in 2D Environments," 2022, doi: 10.1155/2022/5069254.

[24] F. B. Gunay and T. Cavdar, "Kablosuz duyarga ağlarda RSSI, toa ve tdoa yardimiyla gezgin filo lokalizasyon modeli," *2014 22nd Signal Process. Commun. Appl. Conf. SIU 2014 - Proc.*, no. April, pp. 1431–1434, 2014, doi: 10.1109/SIU.2014.6830508.

[25] J. Bardwell, "Converting Signal Strength Percentage to dBm Values," *WildPackets, Inc*, no. November, pp. 1–12, 2002, doi: 20021217-M-WP007.

[26] T. Türkoral, Ö. Tamer, S. Yetiş, E. İnanç, and L. Çetin, "Relative Localization of Wireless Sensor Nodes by Using the RSSI Data," *Netw. Protoc. Algorithms*, vol. 10, no. 1, p. 1, 2018, doi: 10.5296/npa.v10i1.11533.

[27] C. Sommer and F. Dressler, "Using the Right Two-Ray Model? A Measurement based Evaluation of PHY Models in VANETs," *Proc. ACM MobiCom*, 2011.

[28] M. Rezar and F. Ricciato, "On the impact of time-of-departure knowledge on the accuracy of time-of-arrival localization," *Comput. Networks*, vol. 176, p. 107285, Jul. 2020, doi: 10.1016/J.COMNET.2020.107285.

[29] WG802.11 - Wireless LAN Working Group, "IEEE 802.11v-2011 - IEEE Standard for Information technology-- Local and metropolitan area networks-- Specific requirements-- Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications Amendment 8: IEEE 802.11 Wireless Netwo." 2011.

[30] A. Bahr and J. Leonard, "Minimizing Trilateration Errors in the Presence of Uncertain Landmark Positions.," in *Proc. 3rd European Conference on Mobile Robots (ECMR),* 2007.

[31] J. Cheng, J. Cheng, M. Zhou, F. Liu, S. Gao, and C. Liu, "Routing in internet of vehicles: A review," *IEEE Trans. Intell. Transp. Syst.*, 2015, doi: 10.1109/TITS.2015.2423667.

[32] M. S. Varela and M. G. Sánchez, "RMS delay and coherence bandwidth measurements in indoor radio channels in the UHF band," *IEEE Trans. Veh. Technol.*, 2001, doi: 10.1109/25.923063.

[33] L. Schauer, F. Dorfmeister, and M. Maier, "Potentials and limitations of WIFI-positioning using time-of-flight," in *2013 International Conference on Indoor Positioning and Indoor Navigation, IPIN 2013*, 2013, doi: 10.1109/IPIN.2013.6817861.

[34] I. Casacuberta and A. Ramirez, "Time-of-flight positioning using the existing wireless local area network infrastructure," in *2012 International Conference on Indoor Positioning and Indoor Navigation, IPIN 2012 - Conference Proceedings*, 2012, doi: 10.1109/IPIN.2012.6418938.

[35] "RTL8723BU - REALTEK." [Online]. Available: https://www.realtek.com/en /products/communications-network-ics/item/rtl8723bu. [Accessed: 19-Jan-2023].

[36] Y. Sun *et al.*, "Computationally Attractive and Location Robust Estimator for IoT Device Positioning," *IEEE Internet Things J.*, vol. 9, no. 13, pp. 10891–10907, Jul. 2022, doi: 10.1109/JIOT.2021.3127690.