Open Seminar Presentation

on

Energy-Efficient 2D and 3D Localization in Wireless Sensor Networks using Single Anchor Node

Presented by
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Reg. No.: **2016REL01**

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Outline

Introduction

Wireless Sensor Networks

A Wireless Sensor Network (WSN) is a sub-class of wireless network. It is a wireless ad-hoc network between large number of randomly deployed cheap sensor nodes [1]. These sensor nodes are equipped with:

1. Small battery;
2. Sensors (transducers) to record various physical phenomena like pressure, temperature, motion, fire, humidity, etc; and
3. A transceiver to receive and transmit data to and from other sensors and base station (BS).

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Computer networks*, vol. 38, no. 4, pp. 393–422, 2002

Example of WSN

Sensor nodes are deployed randomly in the region.

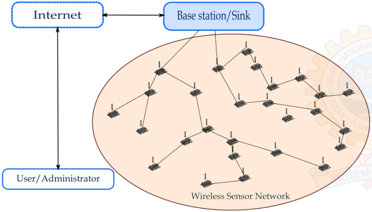

Figure 1: Example of WSN

- These nodes sense physical phenomena (say temp. or pressure).
- They form network and transmit information towards the base station or the sink.
- This sink node can further communicate information to user over Internet.

Sensor node (or mote)

A mote consists of microcontroller board, power supply, antenna, and some sensor.

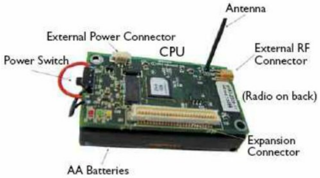

Figure 2: The Mica2 Sensor Node [2]

Figure 3: The Wasp mote

Block diagram of sensor node

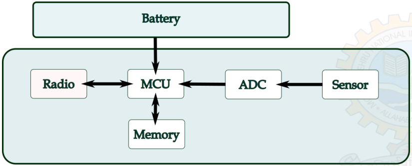

Figure 4: Block Diagram of a sensor node

It has

- MCU to process data and a small memory for storage.
- It has sensor/transducer.
- Radio to communicate over wireless channel.
- Battery to power its operations.

Constraints in WSN

The sensor nodes have limited storage capacity and small computation power, so, they transmit information to Base Station (BS) for processing and operation.

- All operation like sensing, data processing, data transmission and reception consumes power from the same limited battery that the sensor is initially deployed with.
- The sensor node stops working (or die) when the battery power ends, leading to network failures and shortening of network lifetime.
- Further, it is impractical to replace battery of sensors due to large number of sensors typically hundreds (and thousands) deployed in large area, often in harsh conditions.
- Rechargeable solutions are avoided because of cost and size constraints.

Communication protocol in WSN

Energy is the most scarce thing in WSNs, therefore, all the operations and protocols of WSNs are very different from regular wireless Ad-Hoc networks. 6LoWPAN and ZigBee are two major protocols used in WSN communication and both of them operates in 2.4GHz frequency band and can support a data rate of 250kbits/s [3].

- ZigBee is initially developed for low power battery operated device to device communication. It uses IEEE 802.15.4 standard.
- However, ZigBee devices can not easily communicate with other network protocols.
- 6LoWPAN protocol allows devices to communicate with other devices over Internet using Internet Protocol (IPv6) and Low-power Wireless Personal Area Networks (LoWPAN).

[3] X. Wang, "Multicast for 6lowpan wireless sensor networks," *IEEE Sensors Journal*, vol. 15, no. 5, pp. 3076–3083, May 2015

Localization in WSNs

The process of finding the location of sensor nodes is called localization.

- The information gathered by WSNs at the BS is insignificant without the location of sensed region.
- In the absence of location user can not decide proper course of actions.
- Further, many routing algorithms in WSNs depends on the location of sensor nodes.
- Therefore, localization in WSNs is crucial task.
- Inheriting constraints from WSN, localization must be of low complexity and energy efficient.

Anchor nodes and Dumb nodes

Anchor node: It is a sensor node that has knowledge of its location it is commonly referred as *anchor* or *beacon node*.

- These nodes are usually equipped with GPS modules and additional battery.

Dumb node: It is a sensor node in WSN that do not know its location, it is commonly referred as *target*.

- Any Dumb node can act as a anchor node after learning its location.

Classification of Localization

Localization scheme

- Range based or range free
- Anchor based or anchor free
- Single hop or multi hop
- Indoor or outdoor
- Centralized or distributed

Figure 5: A classification of localization schemes in WSNs [4]

Range based or range free

Range based schemes use RSSI [5] or Angle of arrival (AoA) for distance or direction estimation.

- They need additional hardware.
- Direct link with anchor node is required hence categorized as *single hop* localization.

Range free schemes use network connectivity and topology to estimate location of dumb nodes.

- Direct link with anchor node is node not required so there are types of *multi hop* localization.
- These are low complexity algorithms but less accurate [6].

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[5] M. Farooq-I-Azam, Q. Ni, and E. A. Ansari, "Intelligent energy efficient localization using variable range beacons in industrial wireless sensor networks," *IEEE Transactions on Industrial Informatics*, vol. 12, no. 6, pp. 2206–2216, Dec 2016

[6] V. Kanwar and A. Kumar, "DV-Hop-based range-free localization algorithm for wireless sensor network using runner-root optimization," *The Journal of Supercomputing*, Jul. 2020

Anchor based or anchor free

Whether the anchor nodes are required or not.

Anchor based schemes can not work without anchor nodes [5].

- They are accurate in compare to anchor free schemes.
- However, it increases the cost of network.

Anchor free schemes can localize nodes without the need of initial anchor nodes.

- The connectivity and distance between nearby nodes is used for estimation [7].

[5] M. Farooq-I-Azam, Q. Ni, and E. A. Ansari, "Intelligent energy efficient localization using variable range beacons in industrial wireless sensor networks," *IEEE Transactions on Industrial Informatics*, vol. 12, no. 6, pp. 2206–2216, Dec 2016

[7] Y. Zhang, Y. Chen, and Y. Liu, "Towards Unique and Anchor-Free Localization for Wireless Sensor Networks," *Wireless Personal Communications*, vol. 63, no. 1, pp. 261–278, Mar. 2012

Centralized or distributed

Based of processing

Centralized schemes requires accumulation of data from network at BS.

- BS process data and estimate location of each node in network [8].

Distributed localization schemes do not collect data from network at single node.

- Each node in network can estimate its location [9].

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[8] Q. Zhang, J. Huang, J. Wang, C. Jin, J. Ye, and W. Zhang, "A new centralized localization algorithm for wireless sensor network," 09 2008, pp. 625 – 629

[9] Y. Zhang, Y. Lou, Y. Hong, and L. Xie, "Distributed projection-based algorithms for source localization in wireless sensor networks," *IEEE Transactions on Wireless Communications*, vol. 14, no. 6, pp. 3131–3142, 2015

Performance metrics in WSN Localization

Accuracy: The error in localization must be low.

Complexity: The computations at node side must be low. Due to lack of computational power at nodes. Further, each computation consumes energy at the node.

Communication: Number of transmission and reception from nodes must be low. Transmission consumes greater energy than reception.

Energy consumption: The energy consumption at nodes should be low.

Time required: The localization process should be fast.

Hardware: Hardware modifications at node side heavily impact the cost of network, so, it is undesirable.

Energy-efficiency of localization [10]: (η_{loc}) in WSN is defined as.

$$\eta_{loc} = \frac{1/e^2}{E_{loc}}. \tag{1}$$

where e^2 represents (MSE). $MSE = e^2 = \frac{1}{n}\sum_{i=1}^{n}(e_i^2)$.
E_{loc} is the average energy consumed at the nodes in localization process.

[10] K. Zheng, H. Wang, H. Li, W. Xiang, L. Lei, J. Qiao, and X. S. Shen, "Energy-efficient localization and tracking of mobile devices in wireless sensor networks," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 3, pp. 2714–2726, 2017.

Literature review

[11] Chowdhury et al. in 2016

Advances on localization techniques for wireless sensor networks: A survey

- Authors have classified localization schemes as centralized data processing or distributed, range free or range based, static or mobile, indoor or outdoor environment, sparse or dense deployment of nodes.
- It concludes that *range based algorithms are better that range free algorithms*.
- However, the cost of hardware favors range free algorithms.

[11] T. J. Chowdhury, C. Elkin, V. Devabhaktuni, D. B. Rawat, and J. Oluoch, "Advances on localization techniques for wireless sensor networks: A survey," *Computer Networks*, vol. 110, pp. 284–305, 2016

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[12] Yassin et al. in 2017

Recent Advances in Indoor Localization: A Survey on Theoretical Approaches and Applications

- Author presents recent advances in indoor localization where GPS signal breaks.
- It provides comparison on the basis of their cost, complexity, accuracy, security and scalability.
- They have compared the range and the accuracy of various techniques.
- The survey emphasized on the privacy factor in indoor positioning capabilities.
- It concludes that *GPS localization is not good for indoor localization*.

[12] A. Yassin, Y. Nasser, M. Awad, A. Al-Dubai, R. Liu, C. Yuen, R. Raulefs, and E. Aboutanios, "Recent Advances in Indoor Localization: A Survey on Theoretical Approaches and Applications," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 2, pp. 1327–1346, 2017

[12] Yassin et al. in 2017

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[13] Paul and Sato in 2017

Localization in wireless sensor networks: A survey on algorithms, measurement techniques, applications and challenges

- The survey describes various range based and range free localization techniques.
- It presents a comprehensive discussion on different localization-based applications, where the estimation of the location information is crucial
- Further, the challenges such as accuracy, cost, complexity, and scalability are detailed for each application.

[13] A. K. Paul and T. Sato, "Localization in wireless sensor networks: A survey on algorithms, measurement techniques, applications and challenges," *Journal of Sensor and Actuator Networks*, vol. 6, no. 4, 2017

[14] Chelouah et al. in 2018

Localization protocols for mobile wireless sensor networks: A survey

- The authors present the challenges and state of the art of mobile localization in WSNs.
- The study points that there is need for *energy efficient localization*.
- Latency of localization can be reduced.
- Localization must be *low-cost* and *3D localization is better that 2D localization*.

[14] L. Chelouah, F. Semchedine, and L. Bouallouche-Medjkoune, "Localization protocols for mobile wireless sensor networks: A survey," *Computers & Electrical Engineering*, vol. 71, pp. 733–751, oct 2018

[14] Chelouah et al. in 2018

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[15] Laoudias et al. in 2018

A Survey of Enabling Technologies for Network Localization, Tracking, and Navigation

- The authors suggested that to fully exploit the possibilities of localization *the height of target is also required*.
- 2D localization have led to development of various applications but their are *limitations due to their 2D nature*.
- It also covers indoor mobile localization in 5G technology and its future challenges.

[15] C. Laoudias, A. Moreira, S. Kim, S. Lee, L. Wirola, and C. Fischione, "A Survey of Enabling Technologies for Network Localization, Tracking, and Navigation," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 4, pp. 3607–3644, 2018

[15] Laoudias et al. in 2018

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[16] Shit et al. in 2018

Location of Things (LoT): A review and taxonomy of sensors localization in IoT infrastructure

- In this survey, authors present a taxonomy of localization techniques and their feasible application.
- They have compared localization based on merits according to their application in various types of networks.
- A futuristic perspective of localization in IoT-based schemes is also discussed.

[16] R. C. Shit, S. Sharma, D. Puthal, and A. Y. Zomaya, "Location of Things (LoT): A review and taxonomy of sensors localization in IoT infrastructure," *IEEE Communications Surveys and Tutorials*, vol. 20, no. 3, pp. 2028–2061, 2018.

[17] Shit et al. in 2019

Ubiquitous Localization (UbiLoc): A Survey and Taxonomy on Device Free Localization for Smart World

- It presents a review on existing device-free localization (DFL) approaches and their application in the domain of the futuristic smart world.
- Application of DFL is discussed with challenges and futuristic research directions.
- It points the scope of *accurate localization*.

[17] R. C. Shit, S. Sharma, D. Puthal, P. James, B. Pradhan, A. V. Moorsel, A. Y. Zomaya, and R. Ranjan, "Ubiquitous Localization (UbiLoc): A Survey and Taxonomy on Device Free Localization for Smart World," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 4, pp. 3532–3564, 2019

[17] Shit et al. in 2019

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[18] Kumari et al. in 2019

Localization in three-dimensional wireless sensor networks: a survey

- This survey studies the present state of *3D localization in WSNs*
- Its complexity and the scope of research in 3D localization.
- It categorizes 3D localization as: terrestrial, underwater, and underground WSNs.
- The authors also presented a comparison of 2D localization and their advancement as 3D localization
- Further, it compare their performance, complexity, application area and limitations.
- It concludes that 3D localization has gained attention of researchers.
- However, *the proposed algorithms are largely insignificant due to the need of large number of anchor nodes or long computation time*.

[18] J. Kumari, P. Kumar, and S. K. Singh, "Localization in three-dimensional wireless sensor networks: a survey," *The Journal of Supercomputing*, vol. 75, no. 8, pp. 5040–5083, aug 2019

[18] Kumari et al. in 2019

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[18] J. Kumari, P. Kumar, and S. K. Singh, "Localization in three-dimensional wireless sensor networks: a survey," *The Journal of Supercomputing*, vol. 75, no. 8, pp. 5040–5083, aug 2019

[19] Qasim et al. in 2020

Comparison of Localization Algorithms for Unmanned Aerial Vehicles

- Unmanned Aerial Vehicles (UAVs) are used for many applications like security, photography etc. It possesses a threat to privacy and security.
- The author emphasized on security aspect of localization.
- It compares cost, efficiency, range, accuracy, energy consumption and hardware size related to UAV localization.

[19] I. Qasim, N. Habib, U. Habib, Q. F. Usman, and M. Kamal, "Comparison of localization algorithms for unmanned aerial vehicles," in *Intelligent Technologies and Applications*, I. S. Bajwa, T. Sibalija, and D. N. A. Jawawi, Eds. Singapore: Springer Singapore, 2020, pp. 258–269

[20] Zheng et al. in 2011

An improved RSSI measurement in wireless sensor networks

- **Received Signal Strength Indicator (RSSI)** the measurement of the voltage by the receiver's circuit.
- It does not require dedicated packets to be sent over the network.
- The distance (d) between a sender and receiver using the power of the transmitted signal (P_t), the received signal (P_r).

$$P_r(d) = P_t \frac{G_t G_r \lambda^2}{(4\pi)^2 d^2 L}. \tag{2}$$

  here L is loss factor, G is gain, λ is wavelength.
- Error is high due to fading and random attenuation.
- Widely used in localization and distance estimation.

[20] J. Zheng, C. Wu, H. Chu, and Y. Xu, "An improved rssi measurement in wireless sensor networks," *Procedia engineering*, vol. 15, pp. 876–880, 2011

[21] Ward et al. in 1997

A new location technique for the active office

- **Time of Arrival (ToA)** is that instant of time at which the (acoustic) signal first arrived at the receiver (t_2).
- The receiver can compute its distance from the source node if it knows the signal's sending time (t_1) and the propagation speed of the signal in the medium (v).

$$d = (t_2 - t_1)v. \tag{3}$$

- However, this technique requires the clock synchronization between the sender and the receiver.
- The two-way time of arrival uses the round-trip time (RTT) to compute the propagation time between the nodes.
- RTT does not require clock synchronization.
- Error in estimation occurs RTT because of nonuniform processing delay at nodes.

[21] A. Ward, A. Jones, and A. Hopper, "A new location technique for the active office," *IEEE Personal communications*, vol. 4, no. 5, pp. 42–47, 1997

[22] Boukerche et al. in 2007

Localization systems for wireless sensor networks

- **Angle of Arrival (AoA)** requires measuring the angle of arrival of the source signal.
- It rely on *rotation of the directional antennas of the anchor nodes*.
- The receiver computes the time delay between two consecutive received signals from two different emitters and determines the angular distance between them.
- This requires the knowledge of period and phase differences of the revolving antennas of the emitters. The signal from the third antenna helps in computing its 2D position.
- The cost is largely increased by using complex and bulky antenna arrays used for direction measurement at each target node.

[22] A. Boukerche, H. A. Oliveira, E. F. Nakamura, and A. A. Loureiro, "Localization systems for wireless sensor networks," *IEEE wireless Communications*, vol. 14, no. 6, pp. 6–12, 2007

[22] Boukerche et al. in 2007

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[22] Boukerche et al. in 2007

Localization systems for wireless sensor networks

- **TDoA time difference of arrival (TDoA)** requires the computation of the difference between the receiving times of two separate signals sent from the same source node.
$$d = (s_1 - s_2)(t_2 - t_d - t_1). \tag{4}$$
where $(s1, t1)$ and $(s2, t2)$ are speed and time of signal1 and signal2, respectively, and t_d is time delay between two signals at source node.
- Different propagation delays may occur due to different speeds acquired by either signal.
- The additional transmitter-receiver pair requirement at each node for the second type of signal (different frequency) makes the system costly.

[22] A. Boukerche, H. A. Oliveira, E. F. Nakamura, and A. A. Loureiro, "Localization systems for wireless sensor networks," *IEEE wireless Communications*, vol. 14, no. 6, pp. 6–12, 2007

[23] Oguejiofor et al. in 2013

Trilateration based localization algorithm for wireless sensor network

- **Trilateration** is the basic and widely used method in 2D localization approaches.
- It requires the knowledge of distances from three reference points.
- The node computes its position as the intersection point of the circles using radius as the distance between the reference node and the sensor node.
- This technique requires the exact distance measurements to determine the position.

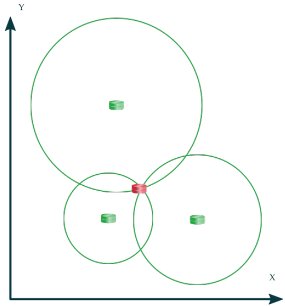

Figure 6: The trilateration method

[23] O. Oguejiofor, A. Aniedu, H. Ejiofor, and A. Okolibe, "Trilateration based localization algorithm for wireless sensor network," *International Journal of Science and Modern Engineering (IJISME)*, vol. 1, no. 10, pp. 2319–6386, 2013

[24] Xu et al. in 2015

An Improved 3D Localization Algorithm for the Wireless Sensor Network

- **Quadrilateration** is the process of finding the position of the target node using the position information of four non-coplanar anchor nodes.
- This method is used in 3D localization approaches.
- The target node estimates its location as the intersection point of the four spheres constructed using the radii.
- This technique requires the exact distance measurements to determine a position similar to trilateration.

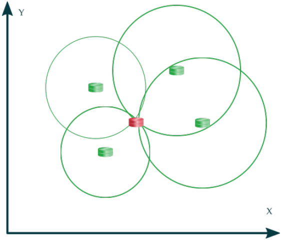

Figure 7: The quadrilateration method

[24] Y. Xu, Y. Zhuang, and J.-j. Gu, "An Improved 3D Localization Algorithm for the Wireless Sensor Network," *International Journal of Distributed Sensor Networks*, vol. 11, no. 6, p. 315714, jun 2015

[25] Wessels et al. in 2010

Dynamic indoor localization using multilateration with RSSI in wireless sensor networks for transport logistics

- **Multilateration** do not require the knowledge of exact distance from anchors.
- However, it requires more than three anchor nodes to construct an overdetermined system of equations for localizing a node in 2D. This technique produces the better result by minimizing measurements' mean square error.
- This technique requires larger number of anchor nodes in comparison with trilateration and quadrilateration.
- High cost of network and energy consumption increases due to large number of communications.

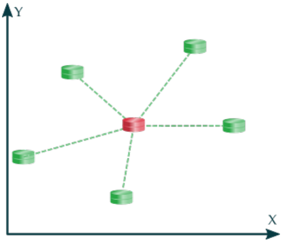

Figure 8: Multilateration

[25] A. Wessels, X. Wang, R. Laur, and W. Lang, "Dynamic indoor localization using multilateration with rssi in wireless sensor networks for transport logistics," *Procedia Engineering*, vol. 5, pp. 220–223, 2010

[26] AbdelSalam and Olariu in 2009

Towards enhanced RSSI-based distance measurements and localization in WSNs

- **Triangulation** uses the angular separation between the anchor nodes and the target node.
- Dumb node use the knowledge of its angle with any three anchors and the locations of anchors which forms a triangle.
- Triangulation and trilateration are similar in nature.
- However, it requires additional hardware for angle measurement between the nodes.

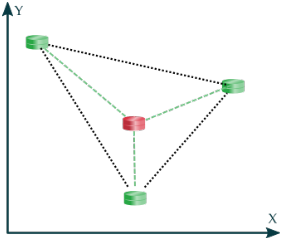

Figure 9: Triangulation

[26] H. S. AbdelSalam and S. Olariu, "Towards enhanced rssi-based distance measurements and localization in wsns," in *IEEE INFOCOM Workshops 2009*. IEEE, 2009, pp. 1–2

[27] Kumar and Lobiyal in 2013

An Advanced DV-Hop Localization Algorithm for Wireless Sensor Networks

- Low cost range free algorithm.
- It do not required any additional hardware.
- Computational cost is low.
- Estimate average hop distance between target nodes in network.
- Then use this average as hop distance to estimate dumb nodes.
- They proposed the use of weighted least square algorithm to further refine location.

[27] S. Kumar and D. K. Lobiyal, "An Advanced DV-Hop Localization Algorithm for Wireless Sensor Networks," *Wireless Personal Communications*, vol. 71, no. 2, pp. 1365–1385, Jul. 2013

[28] Zheng et al. in 2016

A study on application-aware scheduling in wireless networks

- It is an anchor-based, range-free localization algorithm based on the **Distance Vector Hop or DV-Hop** algorithm.
- Uses optimization to improve localization accuracy of DV-Hop.
- Accuracy poor than range based schemes.
- The accuracy depends on uniformity of node deployment density.

[28] X. Zheng, Z. Cai, J. Li, and H. Gao, "A study on application-aware scheduling in wireless networks," *IEEE Transactions on Mobile Computing*, vol. 16, no. 7, pp. 1787–1801, 2016

[29] Wang et al. in 2019

Optimizing Node Localization in Wireless Sensor Networks Based on Received Signal Strength Indicator

- An equal arc triangular location algorithm based on RSSI is proposed.
- Particle swarm optimization is used to further improve accuracy.

[29] W. Wang, X. Liu, M. Li, Z. Wang, and C. Wang, "Optimizing node localization in wireless sensor networks based on received signal strength indicator," *IEEE Access*, vol. 7, pp. 73 880–73 889, 2019

[30] Li et al. in 2019

Cost-Effective Localization Using RSS From Single Wireless Access Point

- It presents a cost-effective localization method by using RSS from single wireless access point (AP) that has only *3 directional antennas*.
- Differential antenna gain is introduced to eliminate the need for known AP-device distances.
- Single anchor is required.
- It do not impact the cost of network as *only one AP is modified*.

[30] Y. Li, K. Yan, Z. He, Y. Li, Z. Gao, L. Pei, R. Chen, and N. El-Sheimy, "Cost-effective localization using rss from single wireless access point," *IEEE Transactions on Instrumentation and Measurement*, vol. 69, no. 5, pp. 1860–1870, 2019

[30] Li et al. in 2019

Cost-Effective Localization Using RSS From Single Wireless Access Point

- It presents a cost-effective localization method by using RSS from single wireless access point (AP) that has only *3 directional antennas*.
- Differential antenna gain is introduced to eliminate the need for known AP-device distances.
- Single anchor is required.
- It do not impact the cost of network as **only one AP is modified**.

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[30] Y. Li, K. Yan, Z. He, Y. Li, Z. Gao, L. Pei, R. Chen, and N. El-Sheimy, "Cost-effective localization using rss from single wireless access point," *IEEE Transactions on Instrumentation and Measurement*, vol. 69, no. 5, pp. 1860–1870, 2019

[31] Naguib in 2020

Multilateration Localization for Wireless Sensor Networks

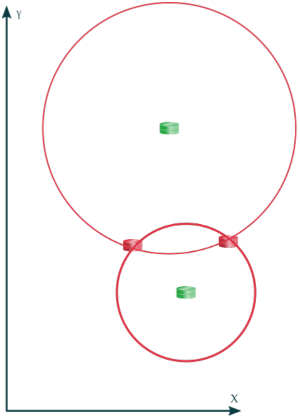
- It is based on multilateration [25].
- A mathematical solution and simulation with NS-2 is shown.
- The author has developed a multilateration module for NS-2 simulator and shared it.

[31] A. Naguib, "Multilateration localization for wireless sensor networks," *INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY*, vol. 13, no. 10, pp. 1213–1223, 2020

[32] Hamouda and Abohamama in 2020

Wireless sensor nodes localiser based on sine–cosine algorithm

- It proposes a sine-cosine algorithm.
- It successfully address the problem of flip ambiguity.
- Results are superior to other optimization algorithms.
- Computation time is reduced.
- Number of node localization is good, However, time of complete localization is high.



[32] E. Hamouda and A. S. Abohamama, "Wireless sensor nodes localiser based on sine–cosine algorithm," *IET Wireless Sensor Systems*, 2020

[5] Farooq-I-Azam et al. in 2016

Intelligent Energy Efficient Localization Using Variable Range Beacons in Industrial Wireless Sensor Networks

- In **Ripple localization algorithm (RLA)**, beacon nodes (BN) vary the transmit power to change the communication radius, starting from R_{min} in uniform steps of R_{step} up to R_c.
- Beacon also contains these values, including the current communication radius (R_i) and the coordinate of the beacon node.
- The nodes in the region will receive multiple beacons with different power levels, and any node can estimate its distance from the beacon node using the values from the first beacon received as $R = R_i - R_{step}/2$.
- Further, multiple beacon nodes are deployed in the region.
- Any dumb nodes after receiving beacons from three or more BNs can solve these distance equations to estimate its location.
- Low accuracy and it requires multiple BNs that increase the cost.

[5] M. Farooq-I-Azam, Q. Ni, and E. A. Ansari, "Intelligent energy efficient localization using variable range beacons in industrial wireless sensor networks," *IEEE Transactions on Industrial Informatics*, vol. 12, no. 6, pp. 2206–2216, Dec 2016

[33] Ou in 2011

A Localization Scheme for Wireless Sensor Networks Using Mobile Anchors With Directional Antennas

- **DIR** uses mobile anchors (BNs) with GPS and four directional antennas each pointing 90° away on the XY plane.
- The anchors are moved on X-axis and Y-axis.
- The anchor nodes transmit beacons with their current location using their DAs.
- Dumb nodes receive these beacon, and select median of all the received x_i's and y_i's as their coordinate.
- This scheme is energy efficient and has low computational complexity.
- However, it requires two or more anchor nodes each having 4 DAs, and these anchors must be moved across the region in two orthogonal directions.
- Further, the accuracy depends on the accuracy of GPS (while moving anchor nodes), beamwidth and orientation of DA.

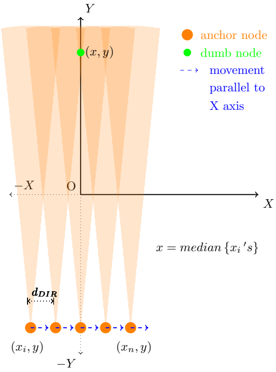


Figure 10: Schematic of DIR.

[33] C. Ou, "A localization scheme for wireless sensor networks using mobile anchors with directional antennas," *IEEE Sensors Journal*, vol. 11, no. 7, pp. 1607–1616, July 2011

[34] Shih and Marrón in 2010

COLA: Complexity-Reduced Trilateration Approach for 3D Localization in Wireless Sensor Networks

- **COLA** converts the complex 3D trilateration in to 2D trilateration using several anchor nodes each having two transmitting antennas placed at different height (named super anchor (SA)).
- The heights of two antennas are same across all anchor nodes.
- Anchor nodes transmit beacons with their location information.
- The dumb nodes estimate their distances with both (upper and lower) anchors using RSSI.
- The distance d with anchor node is estimated as $d = d_2 \sin(\theta)$ and $\theta = \cos^{-1}\left(\frac{d_2^2 - d_1^2 + \Delta h^2}{2 \cdot \Delta h \cdot d_2}\right)$.
- Now, any node with information from three SA and estimate its location (x, y) using 2D trilateration
- The z component is estimated as $z = z_2 - \left(\frac{d_2^2 - d_1^2 + \Delta h^2}{2 \cdot \Delta h}\right)$.

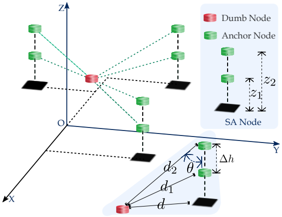


Figure 11: Schematic of COLA

[34] C.-Y. Shih and P. J. Marrón, "COLA: Complexity-Reduced Trilateration Approach for 3D Localization in Wireless Sensor Networks," in *2010 Fourth International Conference on Sensor Technologies and Applications*, no. 2. IEEE, jul 2010, pp. 24–32

[24] Xu et al. in 2015

An Improved 3D Localization Algorithm for the Wireless Sensor Network

- **3D-IDCP**: Here several anchor nodes are placed randomly in 3D space.
- The anchors transmit their locations.
- The dumb nodes receive locations and estimate their distance from each anchor node using the RSSI.
- The dumb nodes test the coplanarity of anchor nodes and select four non-coplanar anchors.
- The dumb node estimates its location by quadrilateration.
- The estimated location is further optimized using the newtonquasi method by converting the localization problem into an optimization problem.

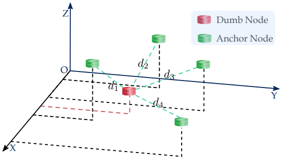


Figure 12: Schematic of 3D-IDCP

[24] Y. Xu, Y. Zhuang, and J.-j. Gu, "An Improved 3D Localization Algorithm for the Wireless Sensor Network," *International Journal of Distributed Sensor Networks*, vol. 11, no. 6, p. 315714, jun 2015

Problem formulation

Problem formulation

It can be concluded from the literature review

1. There is a need of energy efficient localization.
2. The complexity of localization should be low.
3. It should not require hardware modification at the nodes.
4. The number of anchor nodes should be less.
5. It should be free from RSSI based distance estimation.
6. Three dimensional (3D) localization is better than two dimensional (2D) localization.

Problem statement

Problem statement

1. To design a low complexity and energy-efficient localization scheme using single anchor node.
2. To design a low complexity and energy-efficient localization scheme free from RSSI based distance estimation using single anchor node.
3. To design low complexity and energy-efficient three dimensional (3D) localization scheme free from RSSI based distance estimation using single anchor node.

Problem I: Energy-efficient Localization of Sensor Nodes in WSNs using Single Beacon Node

2D localization

- Single Beacon node (SBN) is required for localization.
- The localization process does not require any hardware modification at the dumb nodes.
- The scheme use directional antenna, however, the accuracy is not limited by the beamwidth fo DA.
- Localization is performed in polar coordinates ($R\angle\phi$).
- Two types of beacons are transmitted from SBN, one for Radial distance (R) estimation and another to estimate angle ϕ.
- The nodes act in passive listening mode, so its energy consumption is reduced.

Terms and Notation

Table 1: Terms and Notation

Term	Definition
BN	Beacon Node
SBN	Single Beacon Node
DA	Directional Antenna
WSN	Wireless Sensor Network
P_t	Transmit power from the SBN (or BS)
RSSI	Received Signal Strength Indicator
R	Radial distance from anchor node
R_i	Current communication range of anchor node
R_{step}	Size of increment in communication range of anchor node
R_c	Maximum communication range of anchor node

Assumptions

- SBN and all dumb nodes lie on the same XY-plane ($z = 0$).
- The energy transmitted outside the beamwidth of DA of SBN is zero.
- The nodes start data sensing and routing after completion of the localization process.

Hardware requirements of the single beacon node (or anchor node)

- The SBN needs two transmitting antennas, one Omni-directional antenna and one DA.
- The Omni-directional antenna can vary its transmit power.
- The DA is mounted on a mechanical setup capable of changing its direction in steps of $\Delta\phi$, $\Delta\phi \leq \frac{\phi_b}{2}$.
- The Omni-directional antenna transmits beacons with information to facilitate radial distance estimation (R) from SBN.
- The DA transmits beacons that contain direction information.

Process description

At SBN using omnidirectional antenna

- The SBN use Omni-directional antenna to transmits number of beacons each with different transmit power (P_{t_i}), such that the communication range is R_i ($R_i = i \times R_{step} \mid i \in \{1, 2, \ldots\}$).
- Depending on the distance of any node from SBN, it can receive one or more beacons.
- As shown in Figure 13, when transmitting with $P_{t\,i}$ corresponding to R_i.

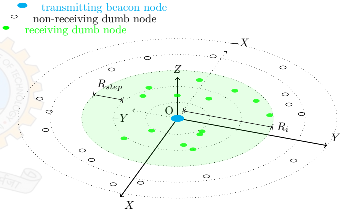


Figure 13: Beacons from Omni-directional antenna of SBN.

Process description

At SBN using omnidirectional antenna

- Nodes with in R_i distance from SBN will receive beacons transmitted with communication range greater or equal to R_i.
- Required power to be transmitted from SBN is

$$P_t = \frac{P_r(4\pi f)^2}{G_t G_r c^2} R_i^2. \quad (5)$$

$$R_{estimated\,i} = \left(R_i - \frac{R_{step}}{2} \right). \quad (6)$$

- The beacon signal contains $R_{estimated}$.

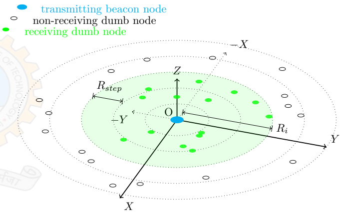


Figure 13: Beacons from Omni-directional antenna of SBN.

Process description

At SBN using omnidirectional antenna

- Total beacons transmitted with Omni-directional antenna is

$$N_R^{TX} = \frac{R_{max}}{R_{step}}. \quad (5)$$

At node side,

- Nodes store the smallest value of $R_{estimated}$ (received in beacon) directly as their radial distance.
- The Maximum error in radial estimation is given by

$$\varepsilon_r \leq \pm \frac{R_{step}}{2}. \quad (6)$$

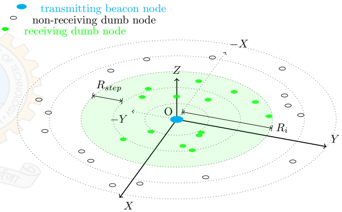


Figure 13: Beacons from Omni-directional antenna of SBN.

Process description

At SBN using directional antenna

- SBN uses one DA with beam-width (ϕ_b), to transmit beacons containing current direction of the DA. The beacon contains only one parameter as ϕ_j.
- The direction of DA is changed in steps of $\Delta\phi$ and a new beacon is transmitted containing current direction ϕ_j.

$$\phi_j = \phi_{j-1} + \Delta\phi = j \times \Delta\phi. \quad (7)$$

$$j \in \left\{0, 1, 2, 3 \ldots \left\lceil \frac{360^\circ}{\Delta\phi} \right\rceil \right\}.$$

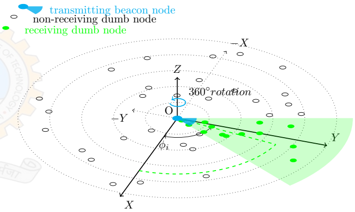


Figure 14: Nodes receiving beacons from rotating directional antenna.

Process description

At SBN using directional antenna

- Any node lying at an angle ϕ_n will receive all the beacons transmitted by DA in the range $(\phi_n \pm \phi_b/2)$.
- Total beacons transmitted from DA is $N_A^{TX} = \frac{360}{\Delta\phi}$.

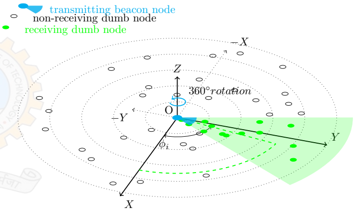


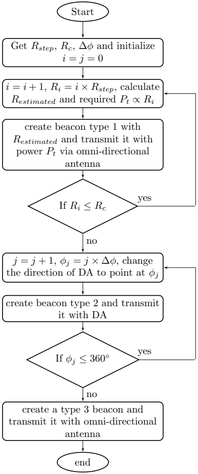
Figure 14: Nodes receiving beacons from rotating directional antenna.

Process description

At node side

- Dumb nodes use values received in beacons and estimate their individual location as
$$\phi_{estimated} = Mean(A). \tag{7}$$
here A is a array of all the values of ϕ_i received by a node.
- Maximum error in $\phi_{estimated}$ is given as
$$\varepsilon_\phi \leq \pm \frac{\Delta\phi}{2}. \tag{8}$$
- Each node has its estimated its location as (R,ϕ), here R is the smallest value received by node in the beacons.
- The location can be converted to (x, y) as $x = R\cos\phi$ and $y = R\sin\phi$.

Flowchart and Algorithm of the process at SBN



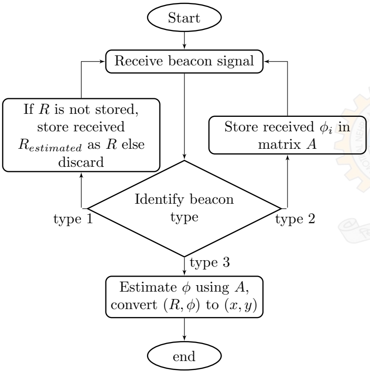
Algorithm 1: Functions of the SBN or BS

Input: R_{min}, R_c, R_{step}, θ_{bw}, $\Delta\phi(\leq \theta_{bw})$.

Output: Transmit updated beacon signal message type 1, type 2 and type 3.

Initialization: Set direction of antenna as $\phi_j = 0°$,
  Set R_{step}=R_{min}.
  /* LOOP Process */
Set $R_i = R_{step}$
while $R_i \leq R_c$ **do**
  Calculate $R_{estimated}$
  Create type 1 beacon message packet containing current values of [$R_{estimated}$]
  Transmit beacon using Omni-directional antenna with power such that its detection range is R_i.
  R_i=$R_{i-1} + R_{step}$
end
/* LOOP Process */
while $\phi_j \leq 360°$ **do**
  Change azimuth angle of antenna such that: $\phi \Leftarrow \phi + \Delta\phi$
  Create type 2 beacon message with updated values. Transmit beacon message using DA.
  Rotate antenna such that: $\phi_j = \phi_{j-1} + \Delta\phi$.
end
Broadcast type 3 (end localization) message.
Broadcast GPS coordinates of SBN (optional).

Flowchart and Algorithm of the process at dumb nodes



Algorithm 2: Functions of any dumb node

Input: beacon signal packet.
Output: (R, ϕ).

```
/* LOOP Process */
while End localization message is not received from SBN. do
    if type 1 message then
        if R is stored then
            Discard beacon.
        else if R is not stored then
            store received R_estimated as R.
        end
    else if type 2 message then
        Store received φ_j in matrix A.
    end
end
Estimate φ using matrix A as equation (7).
Convert to (x, y) ⇐ (R, φ)
```

Energy consumption parameters [35]

used for simulation

Parameter	Notation	Value
Sample rate (packets/sec)	r	1/300
Preamble length (byte)	$L_{preamble}$	271
One byte duration (s)	t_{rxb}, t_{txb}	416E-6
Receive 1 byte current (mA)	C_{rxb}	15
Transmit 1 byte current (mA)	C_{txb}	20
Sample sensing duration (s)	t_{data}	1.1
Sample sensing current (mA)	C_{data}	20
Voltage (V)	V	3
Power consumed in listening radio for preamble (μJ)	E_{sample}	17.3
Sample listening duration (s)	t_{listen}	2.5E-3
Preamble sample interval (s)	t_i	100E-3
Sleep current (mA)	C_{sleep}	0.030

[35] J. Polastre, J. Hill, and D. Culler, "Versatile low power media access for wireless sensor networks categories and subject descriptors," *Proceedings of the 2nd international conference on Embedded networked sensor systems*, pp. 95–107, 2004

Values taken from [35] for Mica2 mote and CC1000 transceiver.

Energy consumption of nodes

Energy consumption (E) of any node can be given as a sum of energy consumed by a node while transmitting (E_{tx}), receiving (E_{rx}), sample sensing date (E_d), listening radio channel (E_{listen}), and sleeping (E_{sleep}) mode.

- These parameters depend on the number of beacons transmitted (n_{tx}), re-

ceived (n_{rx}), and time duration for localization (T_{loc}).

$$E = E_{rx}(n_{rx}) + E_{tx}(n_{tx}) + E_{listen}(T_{loc}) + E_d(n_{sensing}) + E_{sleep}(T_{loc}, n_{rx}, n_{tx}). \tag{9}$$

$$E_{rx}(n_{rx}) = n_{rx} t_{beacon} C_{rxb} V. \tag{10}$$

$$E_{tx}(n_{tx}) = n_{tx} t_{beacon} C_{txb} V. \tag{11}$$

$$E_{data}(n_{sensing}) = n_{sensing} r t_{data} C_{data} V. \tag{12}$$

$$E_{listen}(T_{loc}) = E_{sample} \left(\frac{T_{loc}}{t_i} \right). \tag{13}$$

$$E_{sleep}(T_{loc}, n_{tx}, n_{rx}) = t_{sleep} C_{sleep} V. \tag{14}$$

Equations and values derived from [35] for Mica2 mote and CC1000 transceiver.

Energy consumption at dumb node

The energy consumption at the receiving dumb node is given as

$$N_{total}^{RX} \leq \frac{\theta_{BW}}{\Delta\phi} + \frac{R_c}{R_{step}}. \tag{15}$$

$$E_{dumb} = E_{loc}\left(T_{loc}, 0, N_{total}^{RX}\right). \tag{16}$$

Computational complexity of EE-LSB

- The scheme can be classified as complexity class $\mathcal{P}$.
- By using the uniform cost model [36] the worst case computational complexity at the SBN is estimated as

$$\mathcal{O}\left(N_{total}^{TX}\right). \tag{17}$$

- The complexity at node side is

$$\mathcal{O}\left(N_{total}^{RX}\right). \tag{18}$$

- The computational complexity is linear and independent of the number of nodes in the network.

[36] G. Ausiello, P. Crescenzi, G. Gambosi, V. Kann, A. Marchetti-Spaccamela, and M. Protasi, *Complexity and approximation: Combinatorial optimization problems and their approximability properties*. Springer Science & Business Media, 2012

Simulation parameters and values

Parameter	Symbols	Value
Area (m^2)	A	100×100
Total nodes	n	100
Base-station location	BS	O (0,0)
Beam-width of antenna	ϕ_b	30°
ϕ Step	$\Delta\phi$	10°
Starting position of ϕ	ϕ_{start}	0°
Ripple step (m)	R_{step}	10
Starting ripple radius (m)	R_{min}	R_{step}
Max ripple radius (m)	R_{max}	$R_c(=80)$
Packet length (byte)	L_{packet}	17
Beacon transmission step (DIR) (m)	d_{DIR}	10
Beamwidth of DA (LBRD)	ϕ_{BW}	20°
Height of DA (LBRD) (m)	h	13

Simulation results

The errors lie within the range $\pm R_{step}/2$.

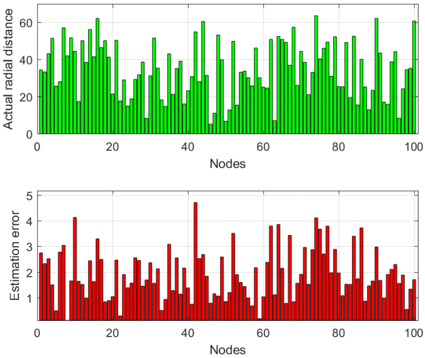


Figure 15: Actual radial distance of the node and the error in their radial estimation.

The error is not related to actual radial distance and lies with the range $\pm R_{step}/2$.

Simulation results

Angle error lies within the range $\pm\Delta\phi/2$

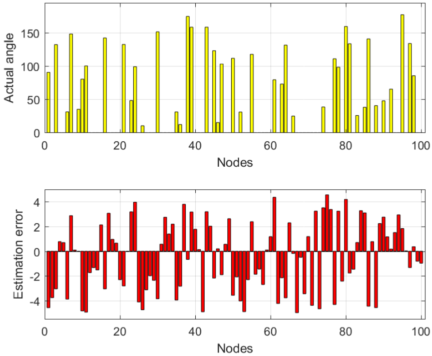


Figure 16: Actual angle distance of the node and the error in their angle estimation.

Simulation results

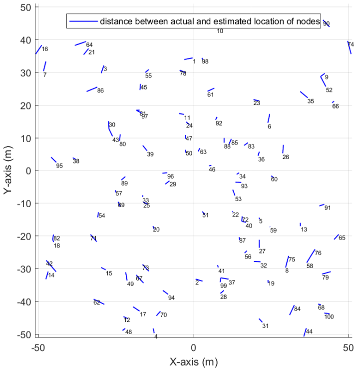


Figure 17: Error distance between the actual node location and the estimated location.

The line represents the distance and direction between the actual location of the node and its estimated location for all the nodes on XY-plane.

Performance evaluation

Performance evaluation of RLA, DIR, LBRD, and EE-LSB

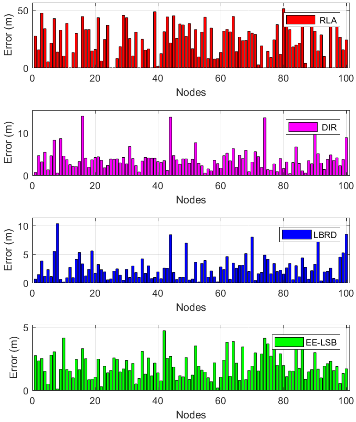


Figure 18: Comparison of error distance

Performance evaluation

Performance evaluation of RLA, DIR, LBRD, and EE-LSB

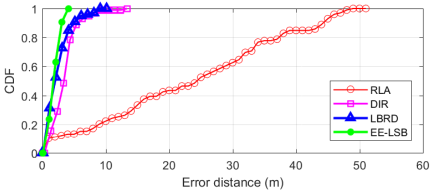


Figure 19: CDF of error distance

- EE-LSB performs better than RLA and close to LBRD and DIR.

Performance evaluation

Performance evaluation of RLA, DIR, LBRD, and EE-LSB

	RLA	DIR	LBRD	EE-LSB
Number of dumb nodes	90	100	100	100
Number of BN	10	2	1	1
Number of DA at each BN	0	4	1	1
Number of onmidirectional antenna at each BN	1	0	0	1
Total beacons transmitted by BN	200	80	360	56
Localization time T_{loc} (s)	20	8	36	5.6
Total beacons received by dumb nodes	8148	400	376	1379
Average beacons received by dumb nodes	90.53	4	3.76	13.79
Energy consumed in transmitting by all BN(J)	0.51	0.004	0.019	0.003
Energy consumed in receiving by all dumb nodes (J)	0.68	0.218	0.954	0.17
Total energy consumed by all nodes including BNs (J)	1.19	0.222	0.972	0.172
Maximum localization error (m)	51.31	0.68	10.33	4.71
Average localization error (m)	23.53	0.68	2.53	1.93
MSE	767.47	0.47	10.55	4.67
Energy-efficiency of localization [10]	0.11	963.18	9.75	124.32

- EE-LSB accuracy is better than RLA although both use RSSI for distance estimation.
- Energy efficiency of DIR appears better because energy consumption in mechanical movement across region in orthogonal paths is ignored.

Conclusion

Problem I

- The proposed localization scheme (EE-LSB) performs better in terms of accuracy and energy consumption.
- It has low computational complexity.
- It requires only one anchor node.
- The total number of beacons transmitted from the beacon node is 56.
- The maximum localization error is less than 4.8m.
- The average localization error is 1.93m.
- The total energy consumption at a node is $0.17J$.

Problem II: Energy-efficient Localization of Sensor Nodes in WSNs using Beacons from Rotating Directional Antenna

2D localization

- In this scheme single anchor node is required.
- It use directional antenna (DA) that can rotate on two axis.
- The anchor node is above ground plane.
- The scheme is independent of RSSI based distance estimation.

Terms and notations

Term	Definition
GPS	Global Positioning System
BS	Base Station
GPS_{BS}	GPS coordinate of BS
DA	Directional Antenna
RDA	Rotating Directional Antenna
WSN	Wireless Sensor Network
P_t	Transmit power from BS
RSSI	Received Signal Strength Indicator
ρ	Radial distance of node from BS
ρ_{max}	Radial distance of farthest node in region that needs to be localized

Hardware modifications required at the Base station for this scheme

i. A directional antenna of beamwidth (θ_{bw}) is placed at height h above BS.
ii. The direction of antenna can be changed to focus on different regions by changing its direction angle ϕ and θ.
iii. The direction of DA can be changed around Z-axis and angle with X-axis is represented by ϕ ($0 \leq \phi \leq 360^\circ$).
iv. The elevation angle θ of antenna can also be changed ($0 \leq \theta \leq \theta_{max}$).

Assumptions taken

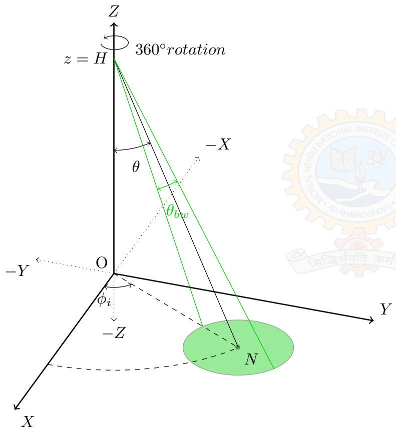


Figure 20: Scheme diagram of proposed scheme

- All nodes lies on XY plane.
- A directional antenna is placed at base-station at height h.
- The directional antenna has beamwidth of θ_{bw}.
- The direction can be changed
  - $0^\circ \leq \phi \leq 360^\circ$
  - $0^\circ \leq \theta < (90^\circ - \theta_{bw})$

Assumptions taken

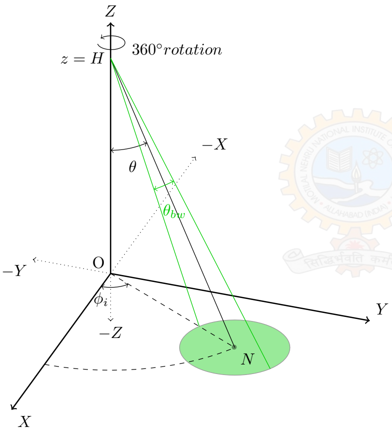


Figure 20: Scheme diagram of proposed scheme

- All nodes lies on XY plane.
- A directional antenna is placed at base-station at height h.
- The directional antenna has beamwidth of θ_{bw}.
- The direction can be changed
  - $0^\circ \leq \phi \leq 360^\circ$
  - $0^\circ \leq \theta < (90^\circ - \theta_{bw})$

Assumptions taken

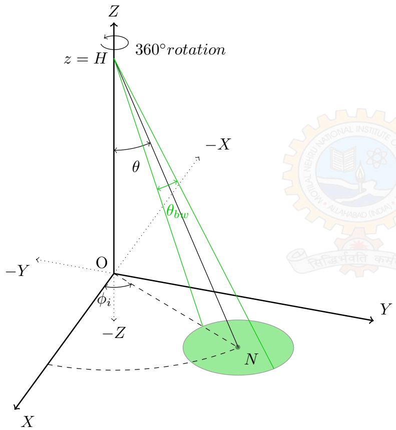


Figure 20: Scheme diagram of proposed scheme

- All nodes lies on XY plane.
- A directional antenna is placed at base-station at height h.
- The directional antenna has beamwidth of θ_{bw}.
- The direction can be changed
  - $0^\circ \leq \phi \leq 360^\circ$
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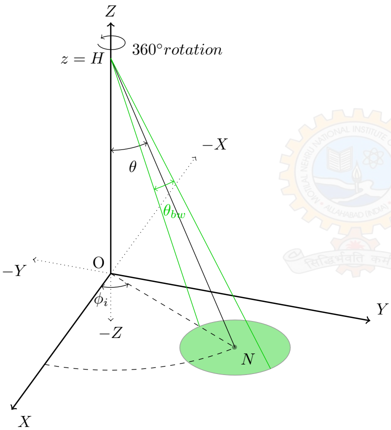
Assumptions taken



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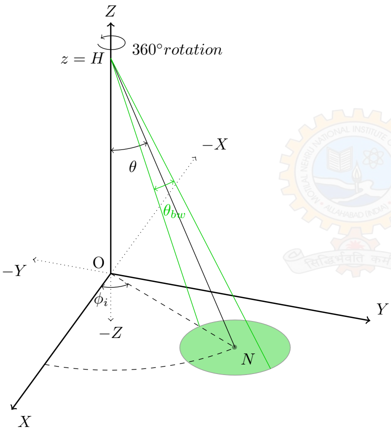

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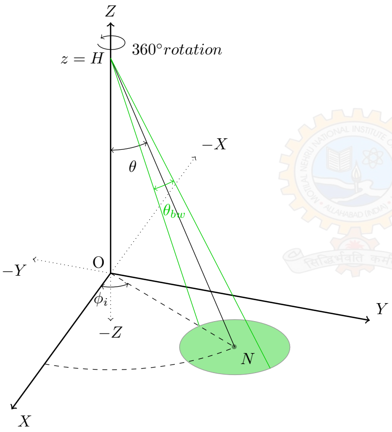

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Effect of changing direction of directional antenna

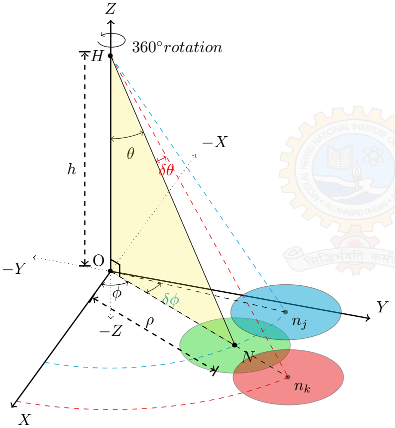
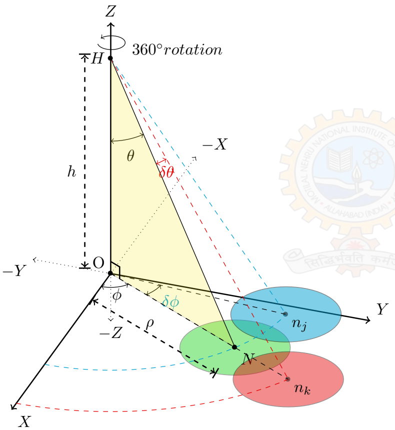


Figure 21: Beam focusing spot changes

- $0^\circ \leq \phi \leq 360^\circ$.
- $0^\circ \leq \theta < (90^\circ - \theta_{bw})$.
- Geometry of importance is shown in yellow color

Effect of changing direction of directional antenna



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Geometry of importance

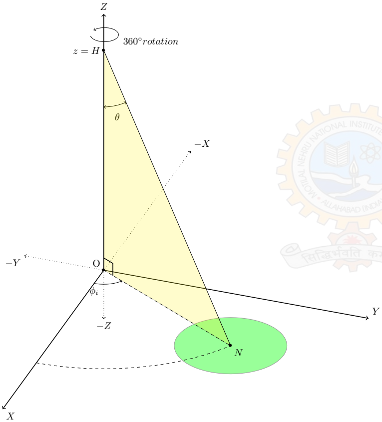
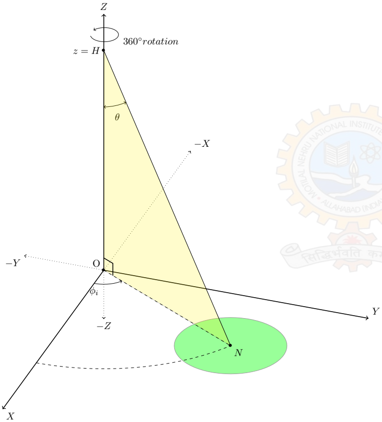


Figure 22: Geometry of importance

- Right angle triangle HON.
- HON lies in the ϕ plane.

Geometry of importance



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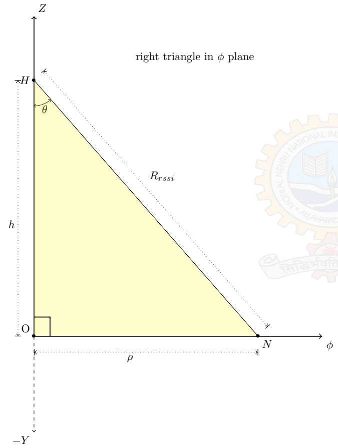
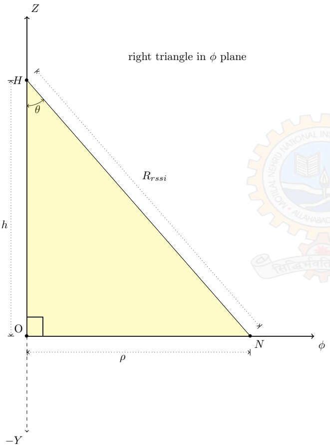


Figure 23: Geometry of importance

- Right angle triangle HON.
- HON lies in the ϕ plane.
- OH$(= h)$
- $\angle$ OHN $(= \theta)$
- ON $(= \rho = h\tan(\theta))$
- Polar coordinate of node N is (ρ, ϕ).

Geometry of importance



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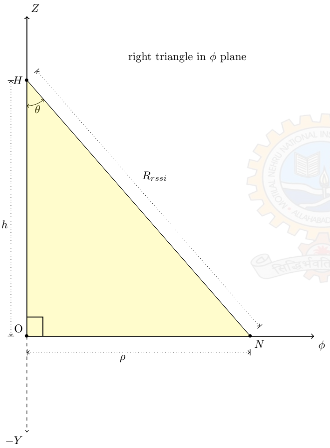

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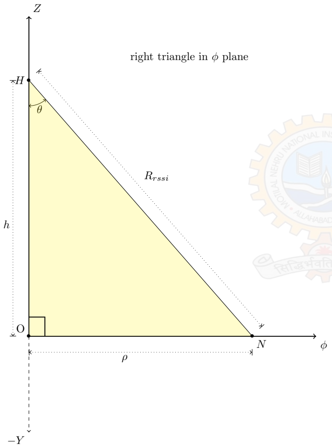

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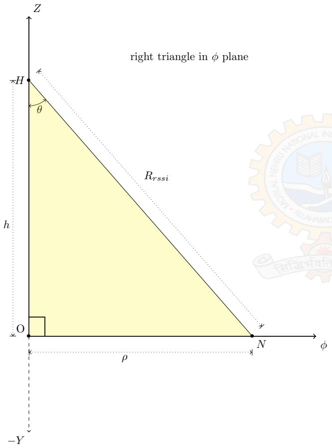

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Content of beacon packet

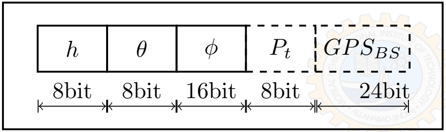
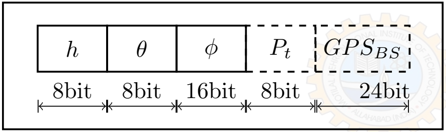


Figure 24: Beacon format

- Necessary components of beacons are
  - h height of antenna
  - θ azimuthal angle
  - ϕ degree of rotation
- Optional components of beacons are
  - P_t transmit power
  - GPS_{BS} coordinate of BS

Content of beacon packet



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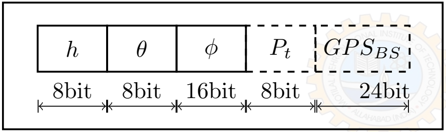

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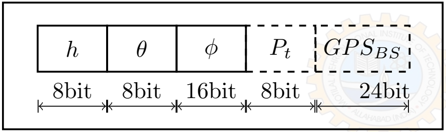

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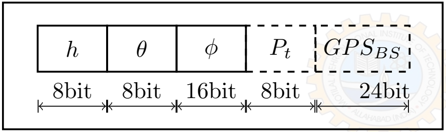

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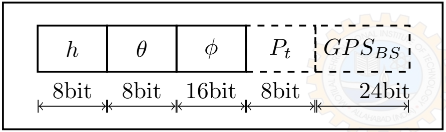

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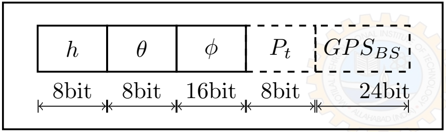

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Process description

At the base station or anchor node

1. Anchor node transmits beacons using its DA after every change in direction.
2. Beacon contains current value of $[h, \theta, \phi]$
3. The ϕ angle of DA is θ_{BW} initially.
4. The DA is first rotated around z axis taking steps of $\delta\phi$.
5. After every rotation the elevation angle of DA is increased by a step of $\delta\theta$ till it reaches θ_{max}.

Process description

At the dumb node

1. Each node is in passive listening mode.
2. Node store valued in beacon
3. Nodes can receive beacons when they are in the beamwidth of DA.
4. At the end of process node takes mean of all the values of beacon and store mean value as its $[h, \theta, \phi]$
5. It estimate its radial distance as

$$\rho = h\tan(\theta). \tag{19}$$

6. Its location is now as (ρ, ϕ) in polar coordinates.

Algorithm: Functions of anchor node or BS

Algorithm 3: Functions of base station

Input: θ_{bw}, ρ_{max}(= distance of the farthest node), h, $\delta_\theta(\leq \theta_{bw})$, and $\delta_\phi(\leq \theta_{bw})$.

Output: Transmit updated beacon signal.

Initialization: Set direction of antenna as $\theta = \frac{\theta_{bw}}{2}$ and $\phi = 0^\circ$.
Create a beacon message packet containing current values of $[h, \theta, \phi, \ldots]$
Transmit it, the packet may include optional components, such as $[P_t, GPS_{BS}]$.
/* LOOP Process */

while $\left(\theta + \frac{\theta_{bw}}{2}\right) \leq \theta_{max}$ **do**
  if $\phi < 360^\circ$ **then**
    Rotate antenna such that: $\phi \Leftarrow \phi + \delta\phi$
  else if $\phi = 360^\circ$ **then**
    $\phi \Leftarrow 0^\circ$
    Change elevation angle of antenna such that: $\theta \Leftarrow \theta + \delta\theta$
  end
  Update values of beacon message packet.
  Transmit beacon message using DA.
end
Broadcast end localization message (using an omni-directional antenna).

Algorithm: Functions of dumb node

Algorithm 4: Functions of a node

Input: Receive beacon signal packet $[h, \theta, \phi]$.
Output: (ρ, ϕ).

/* LOOP Process */

while *End localization message is not received from BS* **do**
    Wait for reception of beacon signal packet.
    $n_{rx} \Leftarrow$number of beacon packet received
    if $n_{rx} \geq 1$ **then**
        if $n_{rx} > 1$ **then**
            $\theta = \sum_{i=1}^{n_{rx}} \frac{\theta_i}{n_{rx}}$
            $\phi = \sum_{i=1}^{n_{rx}} \frac{\phi_i}{n_{rx}}$
        end
        $\rho = h \tan(\theta)$
        Location$= (\rho, \phi)$, relative to BS
        Convert to $(x, y) \Leftarrow (\rho, \phi)$
    end
end

Time required for localization T_{loc}

- N_{total} represents the total number of steps (step means the smallest discrete movement of DA) taken by DA.
- T_a represents time taken by DA to complete one step of $\delta\theta$ or $\delta\phi$ in order to change the direction (alignment) of antenna,
- T_b represents time to update the beacon packet and transmit the beacon signal.

$$T_{loc} = N_{total}(T_a + T_b). \tag{20}$$

$$N_{total} = N_\phi + N_\theta N_\phi. \tag{21}$$

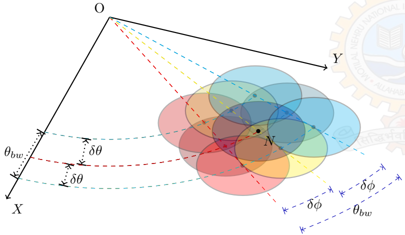
$$N_\phi = \frac{360^\circ}{\delta\phi}. \tag{22}$$

$$N_\theta = \frac{\theta_{max}}{\delta\theta}. \tag{23}$$

- N_{total} represents number of beacons transmitted from BS
- Increasing $\delta\theta$ and $\delta\phi$, T_{loc} and N_{loc} will decrease and energy consumption at the BS will reduce.
- However, it will decrease the localization accuracy.

Number of beacon signal packets received at any dumb node

- The circular spot represents focused region at a distance of $\delta\theta$ or $\delta\phi$.
- The diameter of circle represents the focused spot of beamwidth of DA (θ_{bw}) on XY-plane.



$$N_{rx} \leq \left(\frac{\theta_{bw}}{\delta\theta} \times \frac{\theta_{bw}}{\delta\phi} \right).. \tag{24}$$

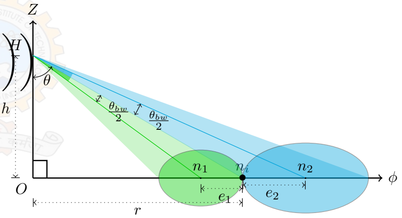
Worst case error

- Maximum error will occur when node receive only 1 beacon packet at the boundary of beamwidth.

$$e = \max(e_1, e_2) \tag{25}$$

$$= \max\left(h\sin(\theta) - h\sin\left(\phi \pm \frac{\theta_{bw}}{2}\right)\right) \tag{26}$$

$$= h\left(\sin(\theta) - \sin\left(\theta + \frac{\theta_{bw}}{2}\right)\right). \tag{27}$$



- It depends on beamwidth of DAs.
- However, final error do not depends on beamwidth of DAs.

Trade-off between h & θ_{bw} for ρ_{max} [theoretical]

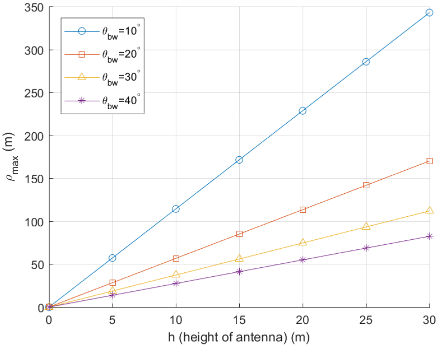


Figure 25: Farthest node that can be localized for given h & θ_{bw}

- h must be increased if θ_{bw} is large.

$$\theta_{max} = \tan^{-1}\left(\frac{h}{\rho_{max}}\right). \tag{28}$$

$$h = \left\lceil \frac{\rho_{max}}{\tan\left(90 - \frac{\theta_{bw}}{2}\right)} \right\rceil. \tag{29}$$

$$\rho_{max} \leq h \tan\left(90 - \frac{\theta_{bw}}{2}\right).. \tag{30}$$

Simulation parameters

Parameter	Notation	Value
Area (m^2)	A	100×100
Number of nodes	n	100
Base-station location	BS	O (0,0,0)
Height of antenna (m)	h	13
Beam-width of antenna	θ_{bw}	20°
Step size	$\delta\theta, \delta\phi$	$5^\circ, 4^\circ$
Initial direction of θ	θ_{init}	0°
Initial direction of ϕ	ϕ_{init}	$\frac{\theta_{bw}}{2}$
Alignment time (s)	T_a	$161.3E-3$
Time to transmit beacon (s)	T_b	$3.87E-04$
Beacon length (bytes)	L_{beacon}	8

- Energy consumption equations are same as previous work.

Simulation results

Node distribution on XY plane

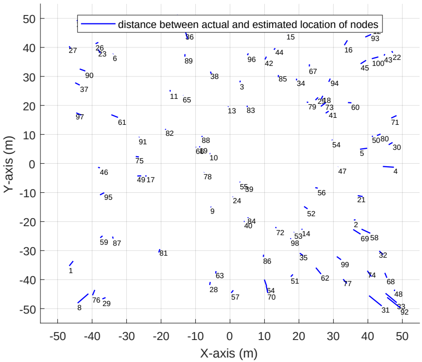


Figure 26: Localization error on XY plane.

- Number represent actual location of node.
- Lines represents error distance and direction.

Simulation results

Convergence of estimated value towards exact value

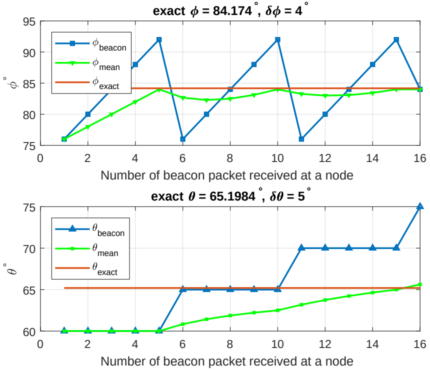


Figure 26: Beacon received value and mean value of θ and ϕ.

- θ and ϕ converges to exact value with time as number of beacons received increases.

Simulation results

Convergence of all nodes

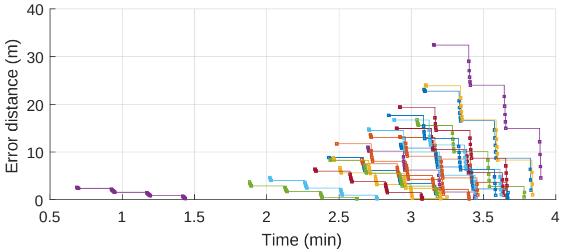


Figure 26: Error converges with time (and number of beacons received).

- Each path represent the value of individual node.
- The error converges for all nodes irrespective of their distance.

Simulation results

Energy consumed at a node

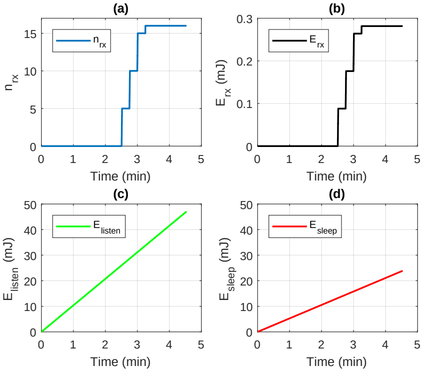


Figure 26: Beacons received and energy consumed by a node.

- If the localization time increases, only E_{listen} and E_{sleep} is affected.

Simulation findings

Parameter	Value
Maximum localization error e_{max}	4.2953 m
Average localization error e_{avg}	1.3101 m
Mean squared error MSE e^2	2.6743 m^2
Energy consumption of a node E_{loc}	0.0689 J
Average energy consumption of all nodes $\overline{E_{loc}}$	0.07 J
Variance of energy consumption $\sigma^2(E_{loc})$	4.0 E-10 J
Localization efficiency η_{loc}	5.4281
Beacons received by a node n_{rx}	16

- Number of beacons received by any node is low.

Performance evaluation

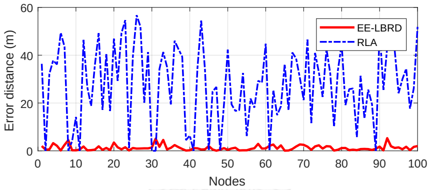


Figure 27: Comparison of localization error of EE-LBRD and RLA.

- Accuracy is better in proposed scheme.

Performance evaluation

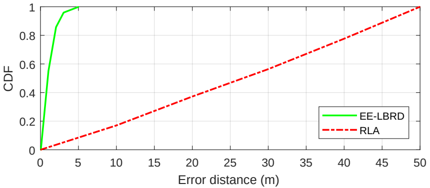


Figure 27: Comparison of cumulative error distribution of EE-LBRD and RLA.

- Maximum error is less than 5m.

Performance evaluation

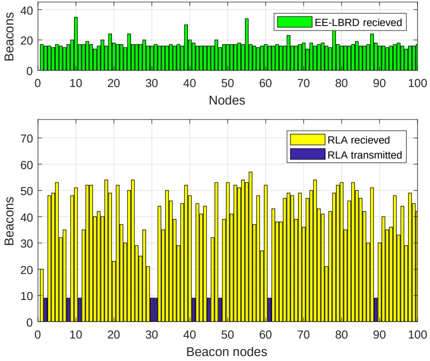


Figure 27: Number of beacons received and transmitted.

- Average beacons received is 18, where as its 48 in related work.
- Number of transmission is 0, where as its average in related work is 10.

Performance evaluation

Comparison of beacons received and transmitted and energy consumption

	EE-LBRD	RLA
Average beacons received	18	48
Average beacons transmitted	0	9
Average energy consumed in receiving one beacon	1.76E-5 J	1.76E-5 J
Average energy consumed in transmitting one beacon	2.35E-5 J	1.15E-5 J *
Total energy consumed by 100 nodes	32.4 mJ	76.8 mJ

* RLA transmit with variable power, so average energy consumption in transmission is half.

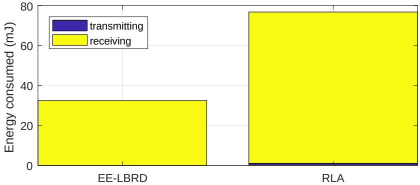


Figure 28: Comparison of total energy consumed by 100 nodes in receiving and transmitting during localization.

- The total energy consumption of nodes is less in compare of related work.

Conclusion

Problem II

- LBRD is capable of localization without any additional hardware component at the node, hence, the cost of the node will not increase.
- The computations required at the node are simple and communication among nodes is not required.
- Localization has been performed with an average accuracy of ± 1.5m and maximum error less than 4.5m.
- Energy consumption of any node during localization is less than 70mJ and energy efficiency of localization is 5.4.

Problem III: Energy-efficient Industrial Inventory Monitoring with 3D Localization of Sensors in WSNs using Beacons from Rotating Directional Antennas

- It is based on previous 2D localization (LBRD).
- This scheme also use single anchor node.
- The anchor node or BS has two directional antennas.
- The anchor node is above ground plane.
- The scheme is independent of RSSI based distance estimation.
- The scheme is verified with MATLAB simulation and validated with hardware setup.
- The shape and dimension of directional antenna is optimized using CST Studio Suite.
- An application is also proposed for monitoring inventory levels in industrial environment.

Video schematic of 3D-LBRD

Anchor node prototype and working (Play in external viewer)

Notations and terminology

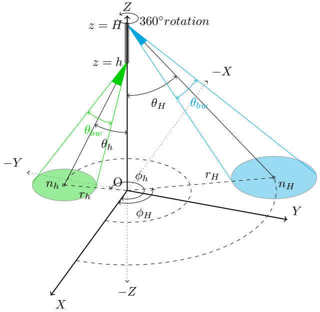
Term	Definition
$3D$	Three-Dimensional
BS	Base Station
DA	Directional Antenna
WSN	Wireless Sensor Network
LOS, $NLOS$	Line of sight, Non LOS
$step$	Change in the direction of DA $\delta\theta$ or $\delta\phi$
r	Radial distance of a node from the BS
h and H	Height of lower and upper DA
θ and ϕ	Elevation angle and rotation of DA
θ_{BW}	Beamwidth of DA
ε	Error in localization (from simulation)

Assumptions

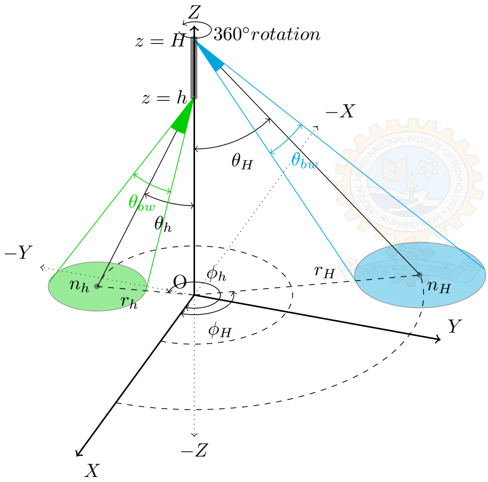
- DA transmits beacons with power (P_t).
- Total power lies inside the beamwidth of the DA.
- The nodes receive LOS signals from the DA. However, NLOS (weak) signals are discarded.

Directional antenna setup at the anchor node of BS

- Similar to previous LBRD, however, here two DAs are used.
- The DAs are placed at different heights (h and H).
- To avoid collisions and interference the direction of DA's is kept at-least θ_{BW} away, thereby, keeping their transmitting region (beam) non-overlapping.
- The ϕ direction of two DA is made $\Delta\phi$ away from each other ($\phi_h = \phi_H + \Delta\phi$ and $\Delta\phi = n\delta\phi$, here $n \in \{1, 3, 5, \ldots\}$).
- The ϕ direction is changed in steps of $\delta\phi'$, ($\delta\phi' = 2\delta\phi$) to avoid redundant transmission on the same ϕ direction.



Schematic diagram of 3D-LBRD



Similar to LBRD.

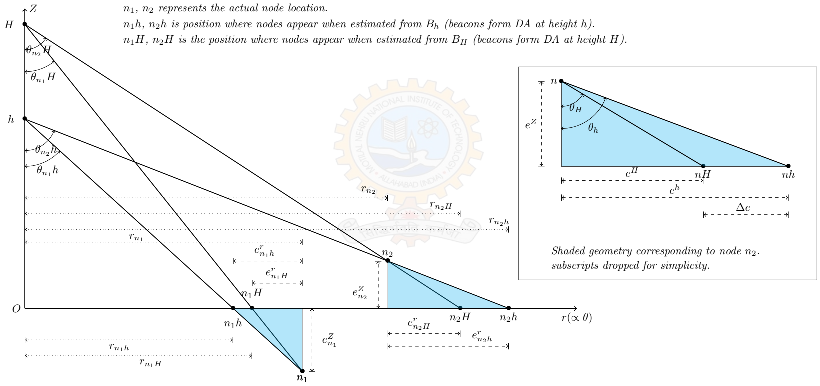
- $r_h = h\tan(\theta_h)$ and
- $r_H = H\tan(\theta_H)$.
- Nodes estimate location using beacon from both DAs and store it in matrix A.

$$A = \begin{bmatrix} h, & r_h, & \theta_h, & \phi_h \\ H, & r_H, & \theta_H, & \phi_H \end{bmatrix}. \tag{31}$$

- Now, the location of a node in 2D in known as (r_h, ϕ_h) or (r_H, ϕ_H).

Schematic diagram of 3D-LBRD

Two dumb nodes n_1 and n_2 at different heights (one below and one above $z = 0$) in same ϕ plane



Error due to variation in z component of node location.

Estimation of z component and correction in radial component

using Δe, ϕ_h, and ϕ_H

$$\Delta e = r_h - r_H. \tag{32}$$

Depending on the position (z-component) of any node, there can be three cases :

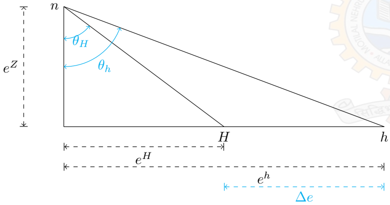


Figure 29: Shaded region of previous slide. (subscripts have been dropped for simplicity).

case i, $z = 0$: $r_h = r_H$ means a zero Δe.

case ii, $z < 0$: $r_h < r_H$ means negative Δe.

case iii, $z > 0$: $r_h > r_H$ means positive Δe.

Estimation of z component and correction in radial component

Equations using Δe, ϕ_h, and ϕ_H

$$\tan(\theta_H) = \frac{e^H}{e^z}. \tag{33}$$

$$\tan(\theta_h) = \frac{e^h}{e^z}. \tag{34}$$

$$\Delta e = e^h - e^H. \tag{35}$$

$$e^z = \frac{\Delta e}{\tan(\theta_H) - \tan(\theta_h)}. \tag{36}$$

$$e^h = e^z \tan(\theta_h). \tag{37}$$

$$e^H = e^z \tan(\theta_H). \tag{38}$$

Now, correction can be applied to radial component and the z value can from be assigned as shown below.

$$r = r_h + \left(e^h\right), \tag{39}$$

$$r = r_H + \left(e^H\right), \tag{40}$$

$$\phi = mean\left(\phi_h, \phi_H\right), \tag{41}$$

$$z = -e^z. \tag{42}$$

Final location is $[r, \phi, z]$.

Process algorithm at BS or anchor node

Algorithm 5: Functions of the base station

Input: θ_{BW}, θ_{max}, h, H, δ_θ, and δ_ϕ.

Output: Generate separate beacon for both DA and transmit updated beacon signal.

Initialization: Set direction of antenna at h as
$\theta_h = \frac{\theta_{BW}}{2}$ and $\phi_h = 0^\circ$.
Set direction of antenna at H as
$\theta_H = \theta_{max}$ and $\phi_H = \phi_h + 180^\circ + \delta\phi$.
Create two beacon message packet containing current values of $[h, \theta_h, \phi_h]$ and $[H, \theta_H, \phi_H]$.
Transmit beacons with respective DA.
while $\theta_h \leq \theta_{max}$ **do**
    if $\phi_h < 360^\circ$ **then**
        Rotate both DAs
        $\phi_h \Leftarrow \phi_h + \delta\phi$; $\phi_H \Leftarrow \phi_H + \delta\phi$.
    else if $\phi = 360^\circ$ **then**
        $\phi_h \Leftarrow 0^\circ$; $\phi_H \Leftarrow \phi_h + 180^\circ + \delta\phi$.
        Change azimuth angle at both DAs
        $\theta_h \Leftarrow \theta_h + \delta\theta$; $\theta_H \Leftarrow \theta_H - \delta\theta$.
    end
    Update both beacon message packet.
    Transmit beacon message using respective DA.
end
Broadcast end localization message (via omnidirectional antenna at BS).

Process algorithm at the dumb nodes

Algorithm 6: Functions of a node

Input: Receive beacon signal packet $[h, \theta, \phi]$.
Output: (r, ϕ, z).

while *End localization message is not received from BS* **do**
    Receive and store beacon packet.
end
Sort all beacons based on first element (height) and store in two matrix: B_h and B_H.
θ_h=mean(θ_i), θ_i is 2nd column of B_h.
θ_H=mean(θ_i), θ_i 2nd column of B_H.
$r_h = h\tan(\theta_h)$; $r_H = H\tan(\theta_H)$.
ϕ_h=mean(ϕ_i), ϕ_i is 3rd column of B_h.
ϕ_H=mean(ϕ_i), ϕ_i is 3rd column of B_H.
ϕ=mean(ϕ_h, ϕ_H).
Save matrix A as shown in (31).
Solve equations (32) to (42) to determine r and z.
store estimated location as $[r, \phi, z]$ (and convert to (x, y, z)).

The computational complexity of 3D-LBRD

The worst-case computational complexity at the node side can be given as

$$\mathcal{O}\left(N_{total}^{RX}\right). \tag{43}$$

The complexity of 3D-LBRD is linear and independent of the number of nodes in the network.

Scheme is of complexity class $\mathcal{P}$ [36]

estimated using the uniform cost model [36]

Simulation parameters

Parameter	Notation	Value
Area (m^2)	A	100×100
Height variation of surface (m)	Z	± 10
Number of nodes	N	100
Base-station location	BS	(0,0,0)
Lower height of DA (m)	h	17
Increment in height of DA (m)	Δh	3
Upper height of DA (m)	H	$h + \Delta h$
Beam-width of antenna	θ_{BW}	20°
Step size *(3D-LBRD i)*	$\delta\theta, \delta\phi, \delta\phi'$	$1^\circ, 2^\circ, 4^\circ$
Step size *(3D-LBRD ii)*	$\delta\theta, \delta\phi, \delta\phi'$	$0.25^\circ, 0.50^\circ, 1^\circ$
Initial direction of θ and ϕ at h	θ_{h_o}, ϕ_{h_o}	$\delta\theta$, 0°
Initial direction of θ and ϕ at H	θ_{H_o}, ϕ_{H_o}	θ_{max}, $180^\circ + \delta\phi$
Beacon packet length (bits)	L_{packet}	8
Anchors in COLA abd 3D-IDCP		15, 30
Height of SA in COLA	z_1, z_2	6.5,13
Degree of irregularity in RSSI	DOI	0.1

- Energy consumption model is same as previous work.

Simulation in Matlab

Node deployment on 3D surface

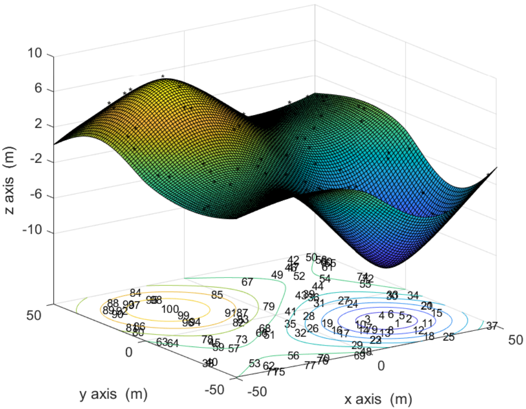


Figure 30: Randomly deployed nodes on the 3D emulated surface.

Simulation results

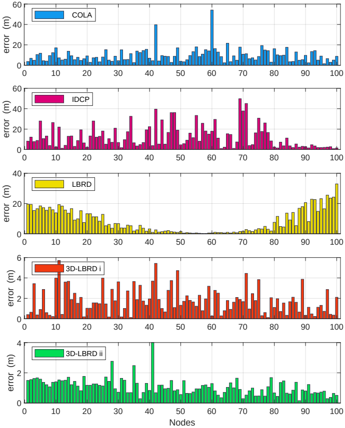


Figure 31: The error distance between the actual and estimated location of the nodes.

Simulation results

CDF of error distance

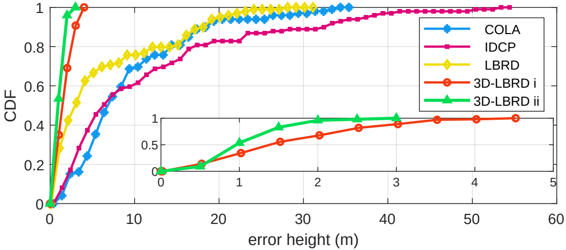


Figure 32: Comparison of CDF of the error distance (after 40 simulations).

- Maximum error in less than 3m, and error in 90% of nodes are localized with an error less than 2m.

Simulation results

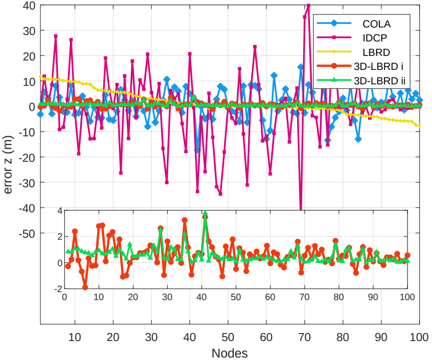


Figure 33: Comparison of error in the estimation of height.

Simulation results

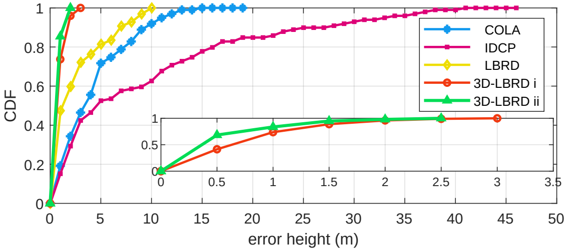


Figure 34: Comparison of CDF of the error in the estimation of height(after 40 simulations).

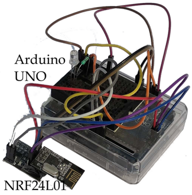
• Maximum error in less than 2.5m, and error in 90% of nodes are localized with an error less than 1.6m.

Error metric from simulation

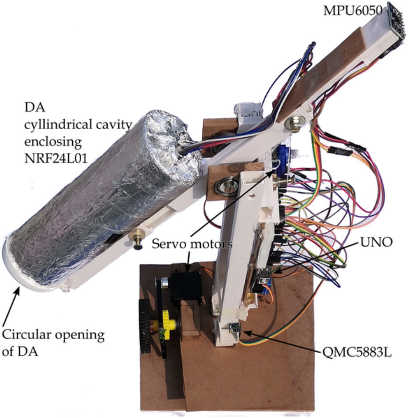
	COLA	IDCP	LBRD	3D-LBRD	
				i	ii
Error distance (m): max, mean, RMSE	54, 9.6, 12	50, 12, 17	33, 8.3, 11	5.7, 1.8, 2.2	4, 1.1, 1.2
Error height (m): max, mean, RMSE	17, 4.8, 6	46, 10, 15	12, 3.6, 4.9	3.5, 0.83, 1.1	3.8, 0.54, 0.77
Number of beacons received at a node N_{rx}	13	25	190	195	3119
Localization time T_{loc} (s)	84	84	1.3E+03	6.5E+02	1E+04
Energy consumption at a node E_{loc} (J)	2.24E-02	2.26E-02	3.48E-01	1.76E-01	2.81E+00
Energy efficiency of localization η_{loc} [10]	0.31	0.16	0.022	1.2	0.24

Hardware setup for experimental validation

Node and anchor node



Node.



BS node or anchor.

Components used

- Arduino UNO (as MCU),
- NRF24L01 (2.4Ghz Radio module),
- GY-521 MPU6050 3-Axis Acceleration Gyroscope,
- GY-273 QMC5883L Triple Axis Compass Magnetometer (to get direction), and
- Two servo motors.

Directional antenna

Simulated using CST Studio Suite, dimensions used

Basic 2.4 Ghz patch antenna with and without conducting circular cavity

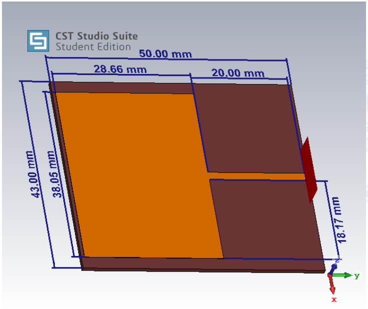


Figure 35: Omnidirectional

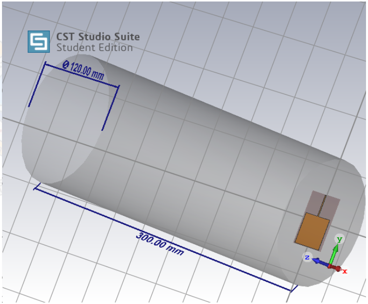


Figure 36: DA using circular cavity

Directional antenna

Simulated using CST Studio Suite, 3D radiation pattern

Basic 2.4 Ghz patch antenna with and without conducting circular cavity

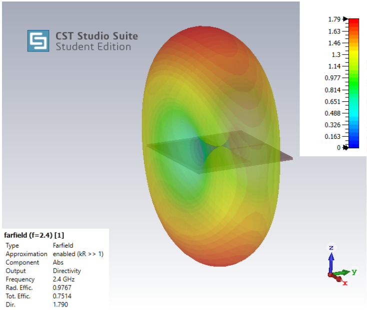


Figure 35: Omnidirectional

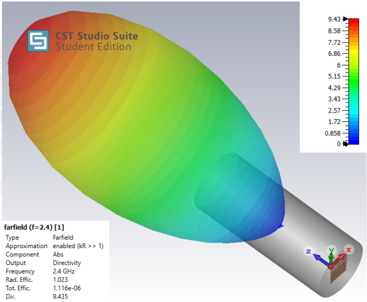


Figure 36: DA using circular cavity

Directional antenna

Simulated using CST Studio Suite, radiation at $\phi = 0^\circ$

Basic 2.4 Ghz patch antenna with and without conducting circular cavity

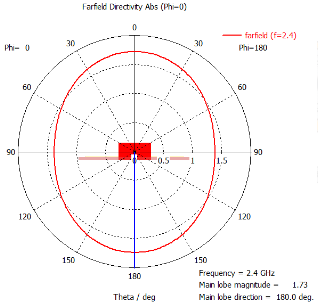


Figure 35: Omnidirectional

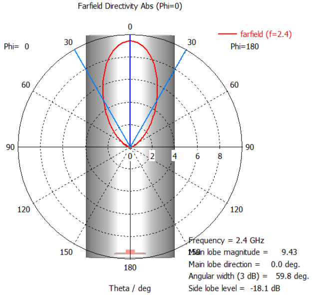


Figure 36: DA using circular cavity

Directional antenna

Simulated using CST Studio Suite, radiation at $\phi = 90^\circ$

Basic 2.4 Ghz patch antenna with and without conducting circular cavity

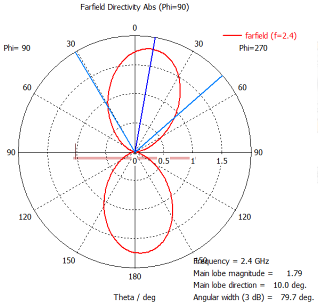


Figure 35: Omnidirectional

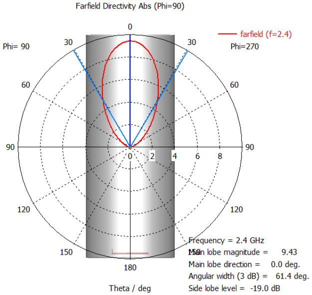


Figure 36: DA using circular cavity

Directional antenna

Simulated using CST Studio Suite, radiation at at $\theta = 90^\circ$

Basic 2.4 Ghz patch antenna with and without conducting circular cavity

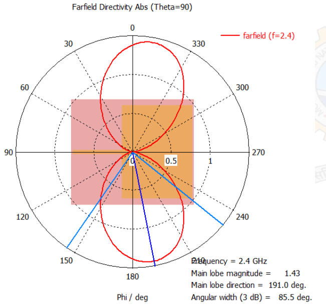


Figure 35: Omnidirectional

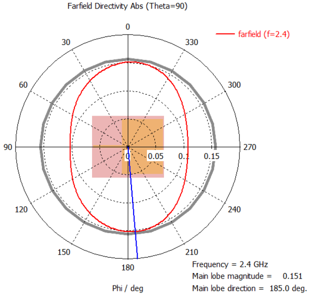


Figure 36: DA using circular cavity

3D radiation pattern of designed DA

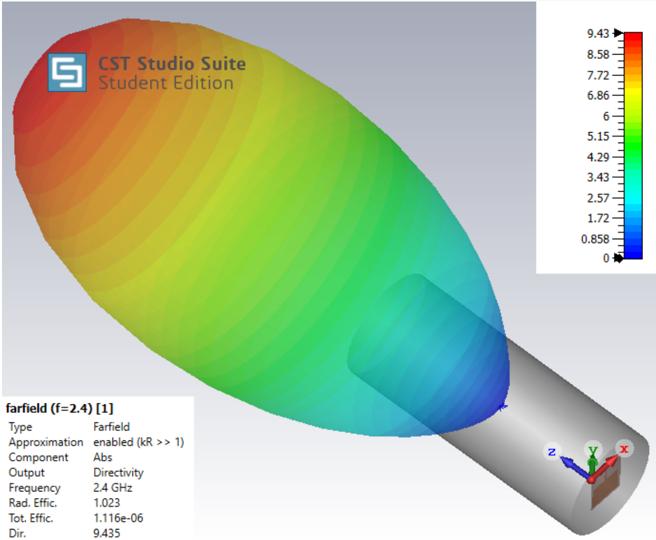


Figure 37: Its beamwidth is around 60°

Experimental setup and results

- Five nodes are placed randomly in a $10m \times 10m$ open space and the height of nodes is varied between $\pm 1m$.
- The height of DAs: $h = 3m$, $H = 4m$ and $\delta\theta = 1^{\circ}$, $\delta\phi = 1^{\circ}$.
- The experiment is repeated four times by changing the location of nodes.

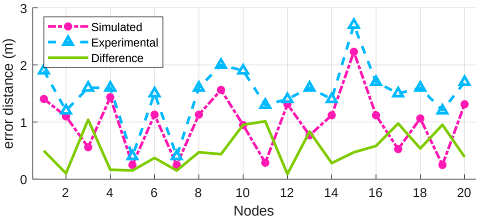


Figure 38: Comparision between experimental and simulated results of 3D-LBRD.

- The maximum difference is less than 1.1m.
- The main source of difference is the offset in the direction of DA and sensitivity of direction detection modules.

Proposed application of 3D-LBRD

3D-LBRD can be used to monitor quantities in various storage tanks with the help of **randomly dropped floating sensor nodes**. *The BS configuration is same as 3D-LBRD ii.*

- Three equal sizes (XY=10m$\times$10m, height in the range $\pm$5m) storage (boiler, fuel) tanks are placed 5m apart in the region (100m$\times$100m).
- The location of these tanks is known.
- Four sensors are dropped randomly in each tank.
- These sensors can float freely above the content inside the storage tanks.
- The sensors are assigned to the nearest tank based on the location of sensors on the XY-plane.
- The level of content in any tank can be calculated by averaging the z component of the sensor nodes inside the tank.

Estimated level of storage tank using 3D-LBRD.

	Tank A	Tank B	Tank C
Location (x, y) (m)	30, 5	30, 20	30, 35
Level (m)	4	0	−4
Node (detected)	[1; 2; 3; 4]	[5; 6; 7; 8]	[9; 10; 11; 12]
Average level (estimated) (m)	4.3	0.4	−3.5
Error in level estimation (m)	0.35	0.4	0.45
Quantity ($V/V\%^*$) error	3.5	4	4.5

* V/V - *volume to volume* .

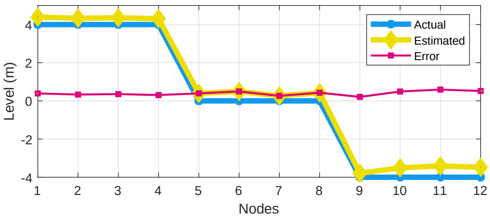


Figure 39: Actual, estimated level and error in estimation using 3D-LBRD.

The error in the z component is less than $0.46m$, and the volume to volume error is below 5%. This technique may be used to monitor resources in any industrial setup.

Conclusion
Problem III

- The energy consumption and complexity at nodes is low.
- The average error is less than 1.1m and RMSE is 1.2m.
- The scheme is verified with MATLAB simulation and validated experimentally with the hardware setup.
- The experimental results prove the concept and the results obtained are close to simulated results.
- Industrial applications of 3D-LBRD, to monitor inventory status is demonstrated with simulation.

Conclusion

Conclusion

Three low complexity, energy efficient localization schemes have been proposed.

1. Each of these schemes use only one anchor node.
2. No hardware modification is required at the target or dumb nodes.
3. No transmission from dumb nodes is required and complexity of schemes is low.
4. Two schemes are independent of RSSI estimation including one 3D localization.
5. The 3D localization scheme is also validated using hardware experimental setup.

Publications

Journals

[1] **P. R. Gautam**, S. Kumar, A. Verma, T. Rashid, and A. Kumar, "Energy-efficient localization of sensor nodes in WSNs using beacons from rotating directional antenna," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 11, pp. 5827–5836, 2019
DOI: 10.1109/TII.2019.2908437, **Impact Factor:** 9.112

[2] **P. R. Gautam**, S. Kumar, A. Verma, and A. Kumar, "Energy-efficient localization of sensor nodes in WSNs using single beacon node," *IET Communications*, vol. 14, no. 9, pp. 1459–1466, 2020
DOI: 10.1049/iet-com.2019.1298, **Impact Factor:** 2.1

[3] **P. R. Gautam**, S. Kumar, A. Verma, and A. Kumar, "Energy-efficient industrial inventory monitoring with 3D localization of sensors in WSNs using beacons from rotating directional antennas," *IEEE Transactions on Industrial Informatics* **Under review**

Journals

[1] **P. R. Gautam**, S. Kumar, A. Verma, T. Rashid, and A. Kumar, "Energy-efficient localization of sensor nodes in WSNs using beacons from rotating directional antenna," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 11, pp. 5827–5836, 2019
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[3] **P. R. Gautam**, S. Kumar, A. Verma, and A. Kumar, "Energy-efficient industrial inventory monitoring with 3D localization of sensors in WSNs using beacons from rotating directional antennas," *IEEE Transactions on Industrial Informatics* **Under review**

Conferences and book chapters

[1] **P. R. Gautam**, S. Kumar, A. Verma, and A. Kumar, "Localization of Sensor Nodes in WSNs using Three Dimensional Angle of Arrival detection at BS," in *2019 International Conference on Electrical, Electronics and Computer Engineering (UPCON)*. IEEE, nov 2019, pp. 1–4

[2] **P. R. Gautam**, S. Kumar, A. Verma, T. Rashid, and A. Kumar, "Localization of sensor nodes in WSN using area between a node and two beacons," in *Advances in VLSI, Communication, and Signal Processing*. Springer, 2020, pp. 221–228

[3] **P. R. Gautam**, S. Kumar, and A. Kumar, "Sensor localization in WSNs using rotating directional-antenna at the base station," in *Advances in VLSI, Communication, and Signal Processing*. Springer, 2021, pp. 705–718

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[4] **P. R. Gautam**, S. Kumar, A. Verma, T. Rashid, and A. Kumar, "Energy-efficient localization of sensor nodes in WSNs using beacons from rotating directional antenna," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 11, pp. 5827–5836, 2019.

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Thank you