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On Propagation Properties of Beacon Based Localization Protocol for Wireless Sensor Networks

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Abstract: In Wireless sensor network (WSN), nodes must be equipped with the feature to self-localize, especially in scenarios where nodes cannot be manually positioned. Localization awareness can enable or benefit a vast array of applications, including intruder detection, tracking physical phenomena, healthcare monitoring and emergency services. Motivated from the results of previous studies, this paper investigates the propagation behavior of beacon based localization using ultra wideband (UWB) based communication systems in WSN. We have designed a beacon-based localization protocol (BBLP) and our experimental results provides the evidence for characterizing the convergence latency and communication cost related to node localization. Through simulation results, we show the effect of location propagation whatever the network size may be. The aim of this paper is to help the researchers in designing the WSNs with appropriate node and network parameters.

Key words: Wireless Sensor Networks · Localization · Two-way Ranging · Trilateration · Anchor Nodes

INTRODUCTION

Today wireless sensor networks (WSNs) are being regarded as a promising option for gathering information from a certain area and delivering it to the base station for decision making. This sensed data is meaningful only if the location of its origin is known. One possible way to localize sensor nodes is to use GPS [1] receivers in sensor nodes but this option cannot be deployed largely because of its cost and considerable power consumption. Usual solution is to equip a limited number of nodes with GPS receivers. These nodes called anchor nodes (ANs) serve as reference for other nodes and help them in their location discovery. These ANs possess the same capabilities including the same transmission range as of ordinary sensor nodes and only help their direct neighbors in getting localized. With respect to location estimation, several authors have reported on the feasibility of two-way ranging (TWR) using ultra-wide band (UWB) communication [2],[3] and an addendum to the IEEE 802.15.4 standard[4] includes this function. TWR based tri-or multilateration enables network wide localization in which the sensor network starts with a limited number of anchor nodes (ANs) with known positions that serve as references to other unlocalized nodes (UNs). In this paper, we have presented a localization algorithm, beacon based localization protocol (BBLP), that make use of two way ranging using ultra-wide band communication. We are only interested in analyzing the localization wave that propagates across the network. While this wave moves, we study the way in which unlocalized sensor nodes (UNs) become localized nodes (LNs). The main motivation behind this work is, that the propagation behavior plays an important role in designing WSN layout and there does not exist sufficient work in the literature that addresses such issue.

Related Work

Localization of Sensor Networks Involve Many Techniques of Distance Estimation Like: Time of Arrival: (TOA) [5], Angle of Arrival (AoA) [6], Time Difference of Arrival (TDOA) [7],[8],[9] Received Signal Strength indicator (RSSI)[10] and RSS profiling [11]. A detailed over view of each of these techniques can be found in [12]. Many of them are not suitable for wireless sensor networks[13]. For example, it has been proved that the AOA method is practically not usable on sensor nodes since it requires highly directional antennas.

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The TDOA technique again requires highly directional, expensive and energy consuming ultrasonic transducers to be deployed on cheap sensor nodes, while the propagation speed of sound depends on external factors like temperature and humidity. The RSS technique is a poor range measurement technique since it gives the distance estimates with 50% accuracy only and the TOA which is one way measurement of the signal propagation time requires synchronized clocks, which is difficult to obtain on energy constrained and cheap sensor nodes. Recent advancements in the ultra-wide band technology and chirp transmission [14] makes the roundtrip propagation time measurement a feasible technique for ranging in wireless sensor networks [15],[16],[17]. Two-way ranging presents several advantages [18]: it does not require additional hardware or synchronized clocks and gives reliable estimates [19]. Moreover, it becomes practically deployable with its specification in the 802.15.4 standard [4]. Studies in [20] have focused on the UWB based ranging feasibility in the presence of various sources of error like multipath fading, clock drifts and interferences. Once we have a possibility of measuring distance between two nodes, a node can determine its position with respect to the positions of the other nodes through tri-or multi-lateration. Then, it needs to propagate the localization information in the network so that all nodes become localized. Many authors have proposed cooperation protocols for such a network wide localization. In this regard, Savvides *et al*. have proposed an iterative beacon nodes based protocol using ultrasonic ranging [8]. Nawaz *et al*. have defined a cooperative protocol to localize the entire network in a local coordinate system with virtual coordinates [9]. Shin *et al*. have introduced a cooperative localization method that symmetrically performs multiway ranging in two phases to improve accuracy of localization [21]. Wang *et al*. [22] propose a WSN localization approach using received signal-strength (RSS) measurements. They have reformulated the problem under the equivalent exponential transformation of the conventional path loss measurement model and the unscented transformation (UT) and is approximately approached by the maximum likelihood (ML) parameter estimation. Shamsi *et al*. [23] have used the semi definite programming technique for WSN localization. They have analyzed and determined new su?cient conditions and formulations that guarantee that the Semi DP relaxation gives the correct solution. These conditions can be useful for designing sensor networks and managing connectivities in practice. Prasan *et al*. [24] have proposed algorithms to localize newly deployed sensor nodes with the help of few beacons and anchor nodes. They have designed analytical methods to calculate and reduce the localization error using probability distribution function. However, these works deal with the WSN localization targeting let's say *x* percent of accuracy. We, on the other hand study the propagation behavior of our proposed localization method. Keeping in view the nature of our study, literature related to the information propagation aspect needs to be discussed as well. To the best of our knowledge, propagation of localization process has not been studied before. However, many works in literature present studies based on other global phenomena occurring in WSNs. Authors in [25] have presented their study about the global phenomena like node reach ability with probabilistic flooding, ad-hoc network connectivity and sensor network coordination. They argue that a good understanding of phase transition phenomena related to the aforementioned activities could provide useful design principles for distributed wireless networks. Work presented in [26] has modeled the WSN as random graph and has proposed a WSN model based on site percolations. The authors have studied the WSN connectivity and energy consumption at the percolation threshold. Research in [27] has mapped probability-based directional and omni directional broadcast to bond and site percolation respectively and have described a collection of directional antenna-based broadcast schemes for mobile ad hoc networks. Work in[28] has proposed a probabilistic approach to compute the covered area fraction at the critical percolation threshold for both coverage and connectivity of a WSN. Besides, [29] have investigated the minimum node degree and k connectivity in wireless multihop networks. Localization in WSNs is made up of mainly two steps: step one involves distance estimation and step two estimates the node positions based on the estimated distances. Among the various available methods of distance estimation, two-way ranging is the most interesting one for low cost and energy constrained sensor nodes. Since, it does not require either accurate clock synchronization or additional hardware. Several authors have reported on its suitability for sensor networks and practical deployment issues[21][17]. Two-way ranging consists in measuring the round-trip time of signal transmission between two nodes. Its accuracy strongly depends on precise recording of emission and reception instants at the physical layer. The MAC layer controls the process by triggering the emission of ranging frames [2] [30].

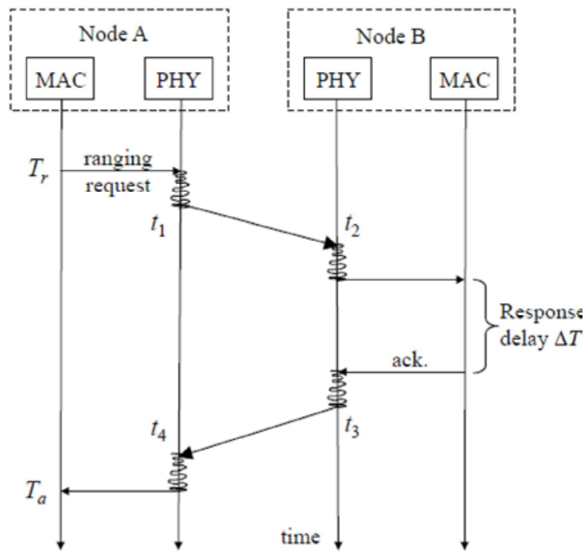

Fig. 1: Principle of Two-way Ranging

Figure 1 illustrates how Node A can estimate the distance based on several timestamps of transmission/reception instants:

$$Di = v.\frac{t_4 - t_1 - \Delta t}{2} \tag{1}$$

In equation (1) v is the propagation speed of the signal (the speed of light for radio signals), t_1 and t_4 are the emission instant (resp. Reception instant) of the ranging frames whereas Ät is the response delay. Since the expression only involves time differences that depend on local clocks, the technique does not require clock synchronization.

BBLP Protocol for Location Propagation: We consider a large scale random 2D sensor network with three non-collinear anchor nodes deployed in the center of the network that we call the *Anchor nucleus*. We assume that the ANs making up the nucleus have overlapping communication ranges. The trilateration process starts by ANs broadcasting beacon messages(BM) with a random inter transmission time. These BM messages are received by the neighboring UNs. Upon receiving three beacons from three distinct ANs, the UNs broadcasts request messages (RMs). For the sake of simplicity, let's consider a single UN broadcasting a RM as shown in Figure 2. This message is received by the entire neighborhood including the three ANs. Each of these ANs then sends a unicast request-response message (RRM) to the demanding UN. AN's response messages bring the anchor node's coordinates plus internal round trip delay

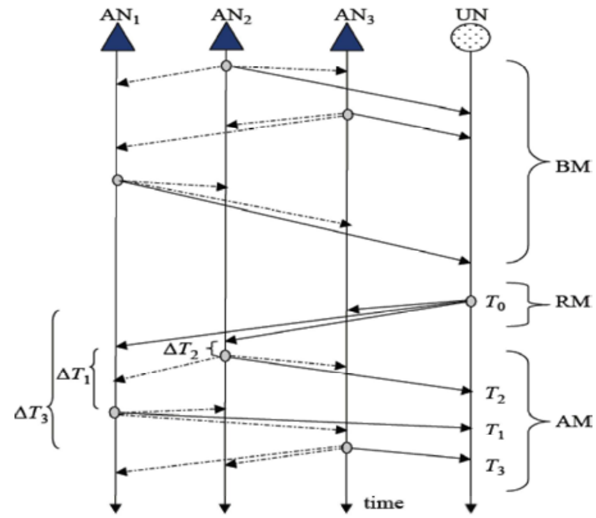

Fig. 2: Principle of Beacon based Localization Protocol

Δt at the AN. Each UN can now estimate its distance from each AN through the formula mentioned in previous section of this paper. The UNs then use these three distances and sets of AN coordinates to estimate their own coordinates in 2D assuming accurate distance estimations. These UNs become LNs and iterate the same process by broadcasting their own BMs. When all the nodes become localized, they start sending beacon messages.

Network Model: Initially, our network S = SAN ∪_SUN, (where SAN represents anchor nodes and SUN represents set of unlocalized nodes). We assume a two-tier network architecture with a set of sensors SUN randomly deployed with a density *ñs* within an area *A* and a set of three anchor nodes deployed in the center of the network to limit the network border effects [31]. Once the localization process starts, our network will become S = SAN ∪_SUN ∪_SLN and later, after the completion of localization process, our network state will become S = SAN ∪_SLN. For each node whether sAN ∈_SAN, sUN ∈_∪_SUN, sLN ∈_∪_SLN, the packet transmission is a Poisson process with an exponential inter-arrival time. The 1-hop neighborhood N1Si, or NSi, of a node in A is the set of all sensors that are in the communication disc centered at si ∈_S with radius rc. A node si ∈_S located at (xi,yi) in A is capable of communicating with another node at location (u,v) in A, if the Euclidean distance d((xi,yi), (u,v)) <= rcsi. Transmission range is the same for all nodes and is set to R meters considering a unit disk graph model. Main parameters for our network are:

$$\rho_s = N / A \quad (2)$$

-Network degree (i.e. mean number of neighbors)

$$\eta = \pi R^2 \quad (3)$$

Given the above data, we derive an analytical expression for the propagation of localization process. *Considering the Spatial Statistics* theory [31], if S^{AN} denotes the set of anchors/localized nodes heard by a sensor *s*, that is, within range *R* from *s*, the probability that *s* hears exactly *k* anchors inside a circle of radius *R* *centered at s*, is given by the Poisson distribution:

$$P(|S^{AN}| = k) = \frac{(\rho_A \pi R^2)^k}{k!} e^{-\rho_A \pi R^2} \quad (4)$$

Based on (4), the probability for every sensor to hear at least three Anchors/Localized nodes is given by:

$$P(|S^{AN}| \geq 3, \forall s \in S) = \left(1 - \sum_{i=0}^{k-1} \frac{(\rho_A \pi R^2) i}{i!} e^{-\rho_A \pi R^2} \right)^{|S|} \quad (5)$$

Let $N^{1}S\ T_d$ denotes the total time delay taken, till the first hop neighborhood gets localized and some of the nodes from first neighborhood have started up with their round of becoming beacon nodes can be written as:

$$N^{1}S\ T_d = t_t^{BM\_1} + N^{1}S_n\ t_r^{RRM\_3} \quad (6)$$

Evaluation: We have used OPNET simulation tool [32], with simple MAC to study our approach. In this section, we evaluate the proposed protocol through simulations and study its convergence as well as other propagation properties.

Experimental Setup: We assume that sensor nodes measure distances by means of two-way ranging and we a large scale sensor network (typically with more than 1000 nodes). For all of our experiments, we consider a network of 1350 nodes. Each point in all of our results is an average of 10 random placements with 25 different simulation seeds.

Convergence: First of all, we analyze the convergence of the propagation process as a function of the average node degree which we vary by adjusting the transmitting power of nodes.

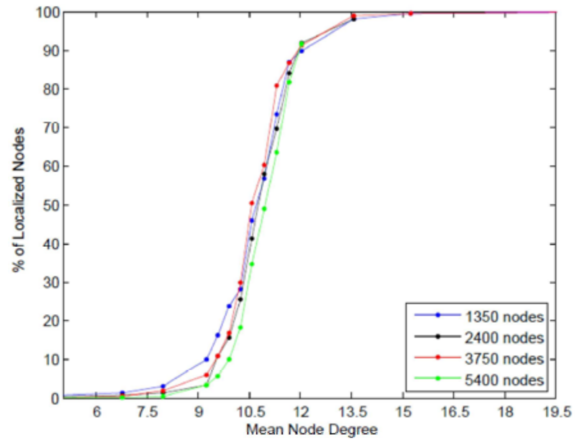

Fig. 3: Critical Node Degree for Varying Network Sizes

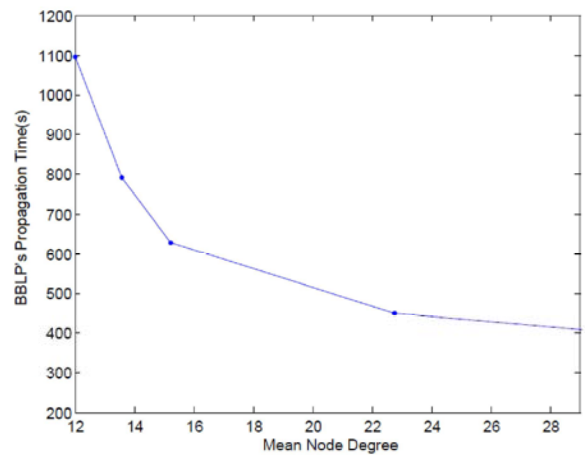

Fig. 4: Mean Node Degree vs; State Change Delay of Last Node

Node Degree vs. State Change Delay: In order for the localization process to converge, we need to have the node degree higher than the critical threshold value i.e. between 10.5 and 11 [33]. Figure 3 shows the BBLP's phase transitions curves with increasing network sizes. These curves show that the critical node degree threshold remains the same (between 10.5 and 11) whatever the network size may be. Based on these results, we are able to predict the node degree required for localizing *x* percentage of nodes using BBLP during practical deployment of a WSN hence economically using each node's precious energy. We are interested in observing the nature of relationship between mean node degree above the threshold vs. state change delay of the last node in the network. We vary the node degree from 12 to 29. We stop at the value of 29 because any further increase in the node degree reduces the number of network hops and the propagation behavior of the protocol remains no longer visible. In figure 4, we observe

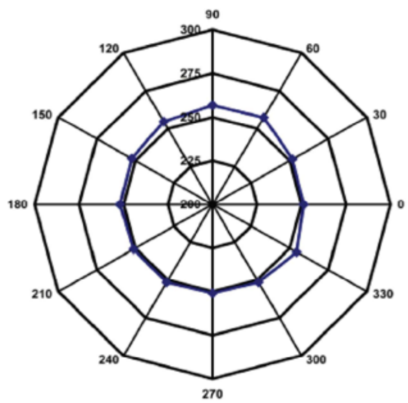

Fig. 5: Isotropic Propagation of BBLP

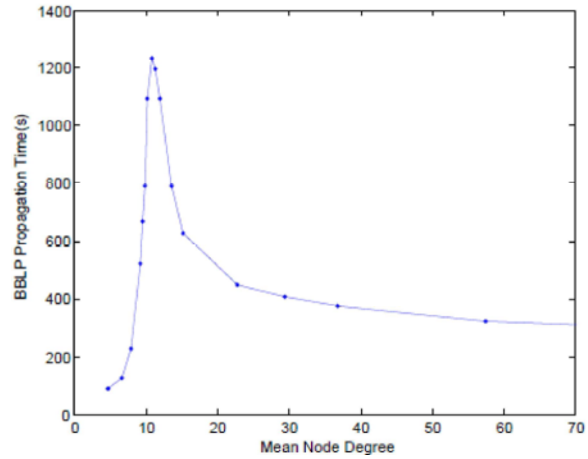

Fig. 6: BBLP's Propagation Time near Critical Node Degree

that the maximum state change delay i.e. the state change delay of the latest node exponentially decreases with increase in the node degree and reaches a stable value for node degree of 22 and above. The reason being, node degree of 14 has already 3-connectivity which is enough to enable BBLP propagation. Further increase in the node degree increase the number of links among already 3-connected nodes which further reduces the time for localization of the network.

Isotropic Propagation: Results in [33] indicate that BBLP propagates across the network isotropically. However, further evidence is needed to prove it. In this subsection, we explain the isotropic propagation of BBLP. We consider a mean node degree of 23 which is just above the node degree after which the protocol's propagation time becomes constant. We take a strip of network area i.e. 100-125m which is right in the middle of the network and note the angles made by nodes situated in this region with respect to the AN nucleus.

We divide the network into 12 parts based on angles and we plot the state change delay of all nodes located in each part. Figure 5 shows that the state change delay in all directions of the AN nucleus are almost the same as is the case with mean state change delay in each section shown with blue circle.

Propagation Time: In this subsection, we investigate the propagation time of BBLP vs. mean node degree. We are interested in observing the protocol's maximum propagation time before the critical node degree i.e. the node degree value of 11. Figure 6 shows that with a small node degree, the propagation time is small since only a few nodes surrounding the AN nucleus become localized. However, it starts to increase with increase in the node degree. It reaches its maximum value near the critical node degree. This behavior of the protocol's propagation time indicates that BBLP spends considerable amount of time propagating the information across links which are barely enough to localize 50% of the network near the critical node degree. This is the point where UNs have to wait the most for getting localized. However, as the node degree increases, the existence of more links than for the previous node degree, the waiting UNs are finally served. Once this critical node degree value is surmounted, BBLP's propagation time starts to decrease. This is because of the increase in the average node degree which starts to render sufficient 3-connectivity required for trilateration. This increases the rate of flow of localization wave.

Communication Cost: We analyze the communication cost of BBLP from two aspects. The first aspect is to analyze the number of transmitted and received packets with respect to increase in distance from the AN nucleus and the second one is, the pattern of each type of packet transmission and reception as a function of mean node degree.

No. of Transmitted and Received Messages: Figure 7 shows the number of transmitted packets vs. distance from the AN nucleus. We consider the transmission range of nodes as 25m making a mean node degree of approximately 29. The packet interarrival time for the three types of packets is set to 5 sec. The BBLP protocol starts it execution 10s after the start of simulation and we terminate the simulation on two conditions: 1)all nodes of the network have been localized

2) in case all nodes have not been localized, the maximum simulation duration (1000sec) is reached. We average the number of transmitted packets by nodes which are located at the same distance from the AN nucleus in all directions. Figure 7 shows that packet transmissions are highest in the vicinity of AN nucleus. This is because; the localization activity starts from here. Even though the localization wave moves forward, the localized nodes that remain behind continue to broadcast BPs till the end of simulation or until all nodes have changed state. Localized nodes get less time to broadcast BPs as compared to the ones near the AN nucleus. Hence, there is a descent in the total number of transmitted packets with an increase in distance from the network center. The linear nature of decrease is due to the linear increase in the state change delay. We see some spreading in the first hop of the network which is due to the presence of non-uniform neighborhood for the unlocalized nodes located there. In the first hop, on one side of the unlocalized nodes, they have a permanent AN nucleus which does not demand for getting localized. However, once the unlocalized nodes become localized and broadcast BPs, they have to send ACKs to the demanding UNs on the other side. We see a different pattern of number of transmitted packets in the first hop since initially, the "localization wave" needs some area to start progressing smoothly. We observe that the order of magnitude of the total number of received packets in more than 10 times than the number of transmitted packets. This is due to the wireless nature of the medium. Besides, the total number of received packets presented here includes all types of packets BP, RPs and ACKs whether they are needed by a node for getting localized or not.

Number of Transmitted Packets vs. Distance from AN Nucleus: We consider two regions of the network: the first hop where the localization activity starts and the fifth hop(i.e. 100-125m) which is right in the middle of the network. Table 1 shows the average number of all packets transmitted in the first and fifth hop. Table values show that nodes in the first hop transmit more ACKs than the fifth hop. Since in the fifth hop, the isotropically propagating wave smoothly progresses outwards. Table also shows that first hop UNs send more RPs than the fifth hop UNs. This is because they receive BPs from the three ANs simultaneously. Hence, they start scheduling their RPs. Since the number of serving nodes is less than demanding nodes in this region; UNs have to broadcast more Rps.

Table 1: Tx packet Count for 1st and 5th Hop

Ist Hop			5th Hop		
BP	RP	ACK	BP	RP	ACK
46	10	21	15	6	15

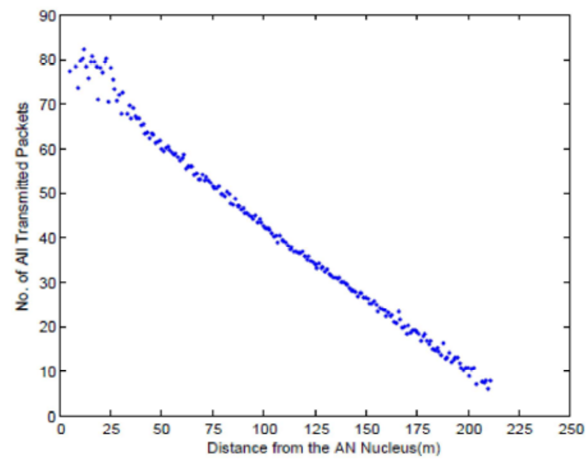

Fig. 7: No. of Transmitted Packets vs. Distance from the AN Nucleus

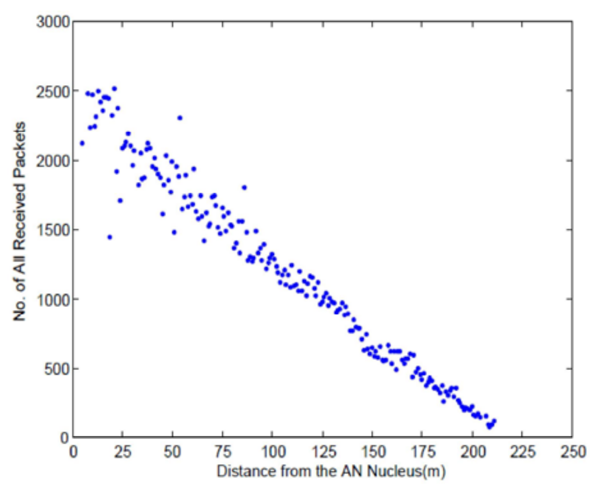

Fig. 8: No. of Received Packets vs. Distance from the AN Nucleus

Number of Received Packets vs. Distance from AN Nucleus: In this subsection, we present the network wide pattern for the total number of received packets vs. distance from the AN nucleus considering the same network parameters as for the number of transmitted packets in the previous subsection. Figure 8 shows the total number of received packets by all nodes of the network. The total number of received packets presented here includes all types of packets BP, RPs and ACKs whether they are needed by a node for getting localized or not.

Table 2: Rx Packet Count for 1st and 5th hop

Ist Hop						
A	B	C	D	E	F	G
14	3	162	61	1399	106	606

Table 3: Rx Packet Count for 1st and 5th hop

Ist Hop						
A	B	C	D	E	F	G
15	3	125	49	451	57	408

We categorize the received packets as follows:

- BPs received by a UN
- ACKs received by a UN that were destined to it
- RPs broadcast by other UNs received by a UN
- ACKs received by a UN that were destined for other UNs
- BPs received by a LN
- RPs received by a LN
- ACKs received by a LN

Table 2 and 3 shows the number of packets received by first and fifth hop nodes. We see more packets in category C of first hop as compared to fifth hop because the UNs in the vicinity of ANs hear the beacons emitted by UNs as a result of which they emit more RPs as compared to the fifth hop. Similarly, more beacons in first hop are because of the presence of ANs over there.

Communication Cost vs. Mean Node Degree: In this subsection, we deal with the behavior of BBLP's communication cost of with increase in the mean node degree. Figure 9 and 10 show this relationship. In figure 9, we see that as we increase the mean node degree of the network, the number of transmitted packets by nodes increase following the same pattern as that of the propagation time reported earlier in this paper. These packets reach their maximum count near the node degree 14 where most nodes of the network possess 3-connectivity required for trilateration and afterwards start to decrease as is the case with BBLP's propagation time. Thereafter, their number continues s to be the same with any further increase in the node degree up to around 100. However, after the value 100, any further increase in the mean node degree increases the number of transmitted packets by nodes. This is because, as we increase the size of neighborhood, more and more UNs receive the BPs broadcast by the ANs/LNs at the same time. As a result, all UNs in the neighborhood of these ANs/LNs start scheduling their RPs simultaneously. These RPs are then broadcast at more or less the same time.

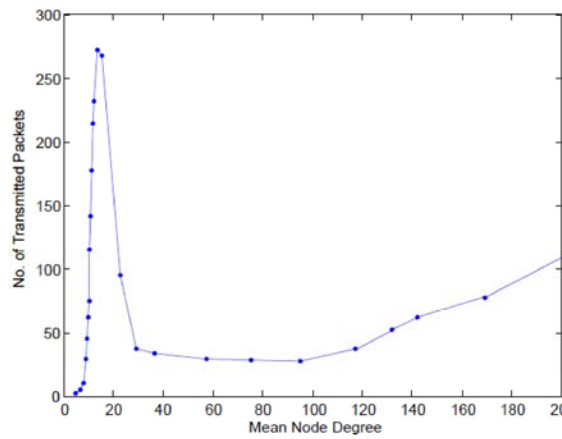

Fig. 9: Mean Node Degree vs. No. of Transmitted Packets

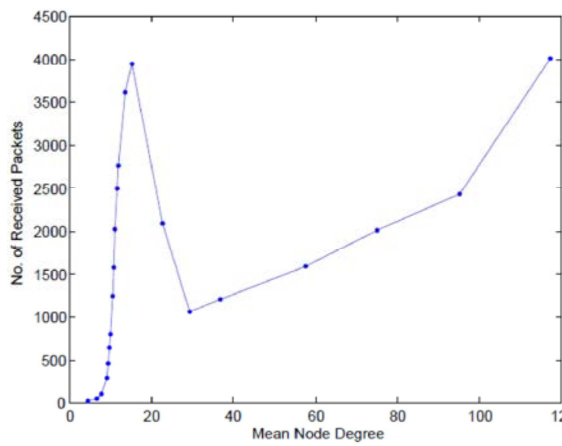

Fig. 10: Mean Node Degree vs. No. of Received Packets

The ANs/LNs receive them at the same time and hence schedule their ACKs for each of the demanding node at the same time. Since the ANs/LNs can only reply the demanding UNs one after the other, before the ANs/LNs can unicast scheduled ACK for one demanding node, that demanding node broadcasts another RP. Since there are multiple demanding nodes at the same time, they all rebroadcast their RPs until they get one ACK from three different LNs/ANs. This process continues and results in increase in the number of transmitted and received packets in the network. Note that this phenomenon eventually increases BBLP's propagation time for a node degree of 100 onwards as shown in Figure 11.

Effect of Additional Anchor Nodes: Researchers working on anchor based WSN localization have always been interested in the effect of number and placement of anchor nodes in the network. Works in this regard forming a non exhaustive list include:[34],[7],[35],[36] and [9].

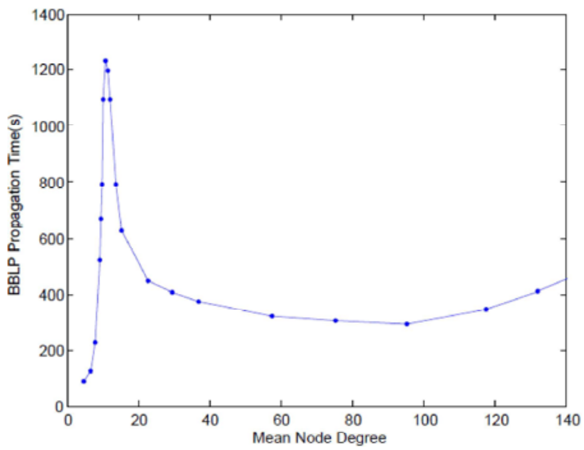

Fig. 11: Increase in Propagation Time vs. Large Node Degree

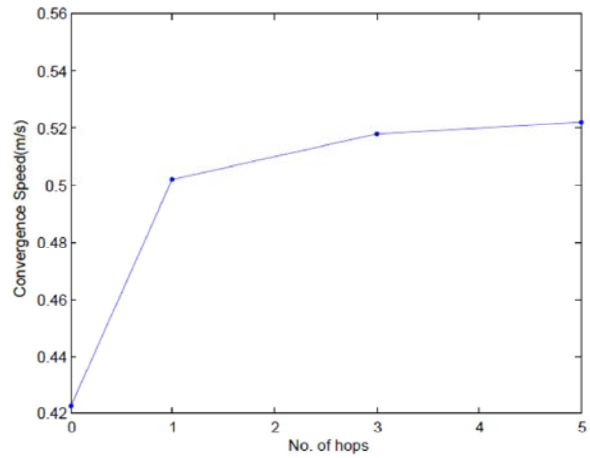

Fig. 13: Convergence speed in the presence of additional anchors

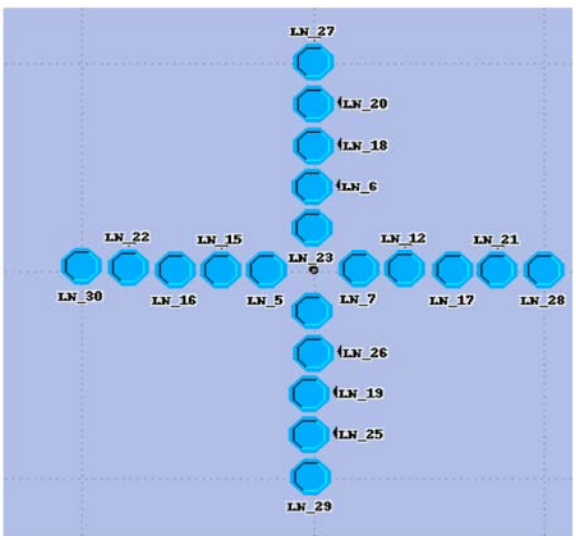

Fig. 12: Placement of Additional Anchor Nodes

All of these works have focused on reducing the position error introduced by placement and percentage of anchor nodes in the network. Since localization error management is not the scope of this paper, we are interested in observing the speed of TWR based BBLP protocol by placing more anchor nodes in the network. An intuitive question that arises here is: how do we place these anchor nodes and how many should we place in the network? As we are interested in the propagation wave that has been generated by the AN nucleus, we do not want to place the additional ANs randomly as by placing them in such way they might create additional nuclei and eventually more waves in the network. Hence, the number of additional anchor nodes should be very small i.e. 1-2% as compared to the unlocalized nodes. We consider each node's transmission range as 25m making approximately 8 hop network. We choose to place additional ANs at each network hop starting from the 1st up to 5th hop as shown in Figure 12. By doing this way, we manage to avoid creating probable more nuclei and focus on the increase in propagation speed of already created wave by introduction of individual ANs along wave's dissemination path. Figure 13 shows the relationship between convergence speed of BBLP vs. additional anchor nodes placed along 1 to 5th network hop. 0 on the x-axis indicates that we only have the original AN nucleus in the network. We have carried out these simulations in the following way: in the first set of simulations, we have placed additional 4 ANs on the periphery of first hop. In the second set, we have placed more ANs on the borders of 2nd and 3rd hop as well. In the third set, we have placed additional ANs along the borders of fourth and fifth hop in addition to the ANs on previous hops. In the Figure, we see that by placing more ANs in the 1st hop, the speed of the BBLP propagation increases by 19%. However, afterwards, with addition of more ANs, there is a nominal increase in speed and it stays constant with further addition of anchors up to fifth hop. One of the possible reason for initial 19% increase in BBLP's propagation speed can be due to the fact that more ANs placed in the communication range of the AN nucleus facilitate the generation and initial propagation of wave while ANs placed along 2-5th hop only help the wave in maintaining its speed. In order to verify this reasoning, we have carried out simulations with additional ANs on second and third network hop only and not on the first hop. We observe similar increase in the convergence speed. The same increase in speed is observed if we place ANs on second, third, fourth and fifth hop and no ANs on the first hop. The convergence speed of the process increases if we place more ANs on the first hop only and on the second hop only. However, if we place ANs on third hop only, fourth hop only and fifth hop only, there is no increase in the convergence speed.

CONCLUSION

In this paper, we have studied the two-way ranging based node localization approach. We have derived an analytical expression for convergence latency of the localization process and have provided simulation results for characterizing the convergence latency and communication cost related to node localization. We have empirically shown that the critical network degree required for location propagation remains the same whatever the network size may be.

We have also observed that the convergence of such process is isotropic across the entire network with and without additional anchor nodes and that there is a maximum limit of increase in the speed of one BBLP propagation wave that cannot be crossed by adding more ANs in the network. In future, we plan to evaluate this approach with a realistic MAC suitable for WSN environment along with multilateration to do position estimation and additional ANs to reduce error propagation.

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