The Insights of DV-based Localization Algorithms in the Wireless Sensor Networks with Duty-cycled and Radio Irregular Sensors

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Abstract*—Location information of nodes is the basis for many applications in wireless sensor networks (WSNs). However, most previous localization methods make the unrealistic assumptions: (i) all nodes in WSN are always awake and (ii) the radio range of nodes is an ideal circle. This overlooks the common scenario that sensor nodes are duty-cycled in order to save energy and the radio range of nodes is irregular. In this paper we revisit the Distance-Vector-based (DV-based) positioning algorithms, particularly, Hop-Count-Ratio based Localization (HCRL) algorithm and investigate the following problems: (i) how is the relationship between the number of sleeping neighbor sensor nodes and the localization accuracy and (ii) how is the relationship between the degree of irregularity (DOI, which is a parameter of radio range irregularity) and the localization accuracy. We conduct a large number of experiments in WSNs' simulator NetTopo, and find that the parameters: the number of waking nodes, DOI, anchor node density and localization error, are interactional, i.e., for a given deployed static WSN, there is an optimal number of waking nodes and an optimal anchor node density, which can minimize network energy consumption without losing much of the localization accuracy. Furthermore, waking up more sensor nodes cannot always help to increase the localization accuracy, which actually is different from our intuitive thinking: more waking nodes can help to increase the localization accuracy of DV-based localization algorithms at all time.

***Index Terms*—DV-based localization algorithms, Duty cycle, Radio range irregularity**

I. INTRODUCTION

GPS (Global Positioning System) is a famous public location service system. However, it is impractical for every sensor node to equip GPS since the high hardware cost. A kind of localization method is proposed as an alternative scheme for identifying sensor nodes' location information in WSNs, in which only a small portion of sensor nodes (anchor nodes) are aware of their position information by GPS or manual configuration [1] and other nodes (unknown nodes) are to be localized. In this kind of localization methods, anchor nodes use the distance vector (DV) routing method to broadcast packages, and the unknown nodes calculate their coordinates based on the number of hops to each anchor node extracted from received packages.

However, most previous DV-based localization methods make the unrealistic assumptions: (i) all nodes in WSN are always awake and (ii) nodes' radio range is regular. They overlook the common deployment scenario where sensor nodes have duty cycle to save energy [2]. In literature [3], Suman Nath *et al.* proposed an efficient decentralized sleep scheduling algorithm connected k-neighborhood (CKN) for making the network be energy saving. With duty cycle, nodes are awake or asleep in each time slot according to the CKN algorithm, which induces the time-varying connectivity (TVC) [3] of network. TVC networks raise positioning issue that has not been presented in the previously-studied work. In a TVC network, a package can be forwarded over the currently waking nodes, but these waking nodes might not provide a shortest path and the number of hops may be increased significantly incurring the coordinate calculation error in DV-based localization algorithms. The Fig. 1 explains this situation. Some researchers propose that the package can be temporarily buffered in intermediate nodes until a better next hop node wakes up. However, the memory of nodes is limited and this approach can cause significant delay. Moreover, in literatures [4] [5], plenty of evidences describe that sensor node's radio shape is irregular, which impacts the further disconnection in a TVC network and in this situation the unknown nodes' calculation accuracy of coordinates is decreased.

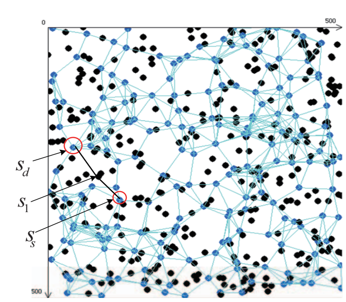


Fig. 1. In the TVC network, the path from node s_s to node s_d is not shortest path. Because node s_1 is a sleeping node (black nodes are asleep and blue nodes are awake), the shortest path $s_s \rightarrow s_1 \rightarrow s_d$ does not exist.

Thus, in this paper, we study an important research problem: *how do duty cycle and radio range irregularity affect the ac-*

curacy of localization in WSNs? Intuitively, when some sensor nodes sleep, since the number of hops from an anchor node to another node is increased, the localization accuracy will be decreased. But existing literatures cannot provide sufficient insights to formally reason about the relationship between sleep scheduling and positioning accuracy. For example, it is not clear how much the error of localization algorithm will suffer if a large scale WSN chooses only 5% of its nodes to keep awake in each epoch (a period of time which keeps the network topology stable).

To reveal the impact of duty cycle and radio range irregularity on DV-based localization algorithms, we conducted large numbers of simulation experiments, in which a sleep scheduling algorithm (CKN) and a DV-based localization algorithm are implemented, with radio range irregular model. Specifically, we analyze the expected increase of positioning accuracy as the number of waking neighbors increase. Our results can be used as tools to select the parameters: the duty cycle of node, the number of anchor nodes and total nodes in a network, the anchor nodes' range ratio and so on for achieving a desired localization accuracy, or to predict localization accuracy for a particular parameter setting. Moreover, we investigate the DOI impact on DV-based localization algorithms and also further research the combined effect of two factors: DOI and k (k is the number of waking neighbors for arbitrary node).

The rest of this paper is organized as follows: we briefly state the related work about the DV-based positioning algorithms, connected k-neighborhood problem and algorithm, radio range irregularity in Section II. In Section III, we state our network model and node's radio range irregular model. Based on these above work, we propose our studying method to investigate the positioning accuracy of HCRL algorithm (HCRL belongs to DV-based typological localization algorithm) in the network that is sleep-scheduling, and node's radio range is irregular in Section IV. We then do some simulation experiments and analyze the results in Section V. Finally, we conclude the paper in Section VI.

II. Related Work

A. DV-based Localization Algorithms

The traditional DV-based localization algorithms (e.g., DV-hop, DV-distance and DV-coordinate all belong to DV-based propagation methods, and if localization algorithms use these propagation methods to propagate the packets, these types positioning algorithms known as DV-based positioning algorithms) for WSNs: the unknown nodes calculate their coordinates using the information packets of anchor nodes which are propagated in network. In DV-based localization algorithms, distance vector (DV)-based routing protocol is used by anchor nodes to find routes for propagating messages, which calculates the distance vectors according to distributed BellmanCFords algorithm [6].

In this paper, we choose the Hop-Count-Ratio based Localization (HCRL) algorithm, which uses only the ratios of anchor-to-node hop counts to do localization and satisfies low cost with a single flooding from a small number of anchor nodes, as a representative of DV-based positioning algorithms and it can be described as follows:

First step: each anchor node broadcasts a flooding message (FM) which includes $Node\_ID$, $coordinate$, and $hopcount$ (HC, and the value of HC is set to 1 in the initialization phase). During flooding, when an unknown node receives a FM, if the FM comes from a new anchor node: the $Node\_ID$ is new, this FM will be stored, or the $Node\_ID$ is already stored, but the HC is less than that received previously, this FM will be updated.

Second step: through the first step, unknown nodes store only one FM which contains the smallest HC for each anchor node and then use Apollonius Circle and hop-count ratio information to do position estimation [7].

B. CKN Algorithm for Sleep Scheduling in WSNs

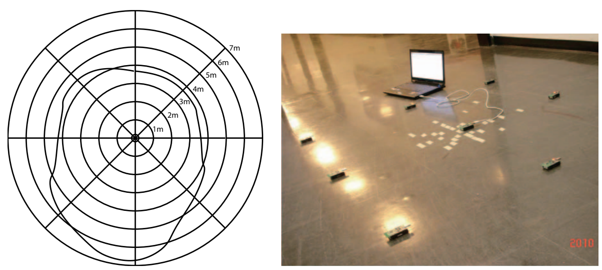
In common scenario, the sensor nodes in a WSN are duty-cycled in order to save energy, we can use CKN algorithm to implement the duty cycle of nodes, which is proposed by Suman Nath *et al.* [3] for solving a connected k-neighborhood problem which has the following two properties: (i) each node v has at least $num = min(k, d_v)$ (d_v is the degree of v in the network; k is the minimum connected waking k-neighborhood which means we need to keep a certain number of neighbors awake) neighbors; (ii) the nodes in the set of waking nodes are connected.

CKN algorithm is distributed and it is repeated at each scheduling epoch and it has an important parameter: randomized node ranks. The ranks are assigned randomly on each epoch and every node maintains some local invariants based on its rank. The CKN algorithm is depicted as follows: the input of algorithm is the value of k, and the value can be chosen depending on the target localization performance. First step, a node u picks a random rank $rank_u$ which can be generated by random number generator. Second step, the node u computes a subset $C_u = (nb_1, nb_2, ..., nb_n)$ of neighbors meeting a condition $rank_{nb_i} < rank_u$. Third step, when the node u wants to go to sleep, it needs to make sure that all nodes in C_u are connected and each of its neighbors has at least k neighbors from the subset C_u (the third step can be also described as: if a node has less than k neighbors, none of its neighbors goes to sleep and if it has more than k neighbors, at least k of them are awake). Moreover, the random numbers are computed randomly on each scheduling epoch, so the set of waking nodes changes from one epoch to another epoch, which ensures that every node has an opportunity of sleep to save energy. In appendix, the CKN algorithm is described in detail.

C. Radio Range Irregularity

In [8], Tian He *et al.*, for the first time, proposed an irregular radio model: DOI model, which assumes an upper bound and a lower bound on the radio propagation range and three communication scenarios: (i)symmetric communication, two nodes in the communication range with each other, (ii)unidirectional asymmetric communication, one node within another node's communication range and the another node is not in the communication range of the one node and (iii)no communication, two nodes without in the communication range with each other. However, the DOI model does not take the interacting of nodes into account. And then the paper [9] extends the DOI model considering the radio interference among sensor nodes and the new model is called as radio irregularity model (RIM). This model is based on experimental results that made with a pair of $MICA2$ nodes and used to analyze the impact of radio irregularity on MAC and routing protocols.

We use the Berkeley mote platform to do some experiments showing the radio range irregularity phenomenon. As an example, the Fig. 2(a) reveals the result when setting power level equals to 5 and the Fig. 2(b) shows our test environment.



(a) The radio range irregularity phenomenon using power level 5

(b) The test environment of radio range irregularity phenomenon

Fig. 2. Radio range irregularity phenomenon tests using Berkeley mote platforms.

III. Models

A. Network Model

In our network model, the $G = (S, E)$ is a communication graph which is directly derived from the WSN topology, where $S = \{s_1, s_2, \ldots, s_n\}$ is the set of nodes (our network has two types of sensor nodes S_a (anchor nodes) and S_u (unknown nodes). Unknown nodes randomly deployed with a density ρ_{S_u} within an area Ω, and a set of specially sensor nodes S_a with known location, also randomly deployed with a density ρ_{S_a}) and E is the set of possible communication links. Each node has transmission radius t_i, so the necessary condition for a successful communication between nodes s_i and s_j is $\|s_i - s_j\| \leq t_i$, where $\|s_i - s_j\|$ is the Euclidean distance between s_i and s_j. However, in our network the nodes are sleep-scheduling and radio-range-irregularity, so the connectivity is time-varied and cannot be guaranteed (even if $\|s_i - s_j\| \leq t_i$, the nodes s_i and s_j maybe cannot communicate with each other).

B. Sensor Node's Radio Range Model

In order to ensure that our evaluation is as true to reality as possible, based on previous studies [8] [9], we build a more general radio model in this paper. In this model, the DOI is an important parameter which describes the grade of radio range irregularity for sensor node and our radio range model is based on IEEE 802.11 wireless Ethernet standard:

First step: determine the value of attenuation according to environment and node type for modeling. In the radio range model, the attenuation parameter ε is important and it is impacted by the environment and type of sensor node. We use the previous related researches [10] [11] to get the attenuation value for our WSN.

Second step: determine the maximum radio transmission range which is related with the transmission power.

Third step: use Formula 1 to calculate the actual transmission range [12].

$$t_i = R_{max} * sin(\pi(0.5 - \frac{1}{N})(rand * \varepsilon * \theta)), t_i \geq 0, \quad (1)$$

where R_{max} is the maximum radio transmission range, N is the number of connected neighbors, $rand * \varepsilon$ is DOI which is a random number based on ε (ε can be set by user) and θ is angle value.

IV. Studying Method and Analysis

A. Our Studying Method

Our studying method is based on CKN sleep scheduling algorithm. Moreover, we implement the HCRL algorithm with CKN and radio range irregularity model. On the basis of this implementation we investigate the impact of sleep scheduling and DOI on localization accuracy.

First, we utilize CKN algorithm to ensure the sleep scheduling of network (CKN algorithm can guarantee that k neighbors of any node are awake), and at the same time also consider the effect of node's DOI (this parameter affects the connectivity of network).

Second, the HCRL algorithm is based on CKN algorithm. Noting that a sleep time is required before or after transmitting a FM in order to save energy, so the CKN sleep scheduling algorithm should be run in every sensor node. Moreover, we need to guarantee that at least k neighbors are awake for every node, which ensures that every anchor node can send a certain number of FMs to other nodes (this can guarantee positioning accuracy of HCRL algorithm), and we can use statistical method which is based on experiments to get an appropriate k value.

B. Our Error Evaluation Method

Estimated error: in this paper, the error means the bias between node's real coordinate and calculated coordinate and we use the formula: $error = \sum_{i=1}^{n} \frac{\Delta r_i}{n R_{max_i}}$ ($\Delta r_i = \sqrt{\Delta x_i^2 + \Delta y_i^2}$ and R_{max_i} is the maximum transmission radius of sensor node s_i) to calculate it. We choose 100 epochs in NetTopo simulator to calculate average estimated error (in this paper, the "average" means: 100 epochs and all nodes average) for the special k value and anchor node density.

Variance of estimated error: in order to reflect the stability of the average estimated error in 100 epochs for localization algorithm, we use variance of estimated error, and computing formula is: $S^2 = \frac{1}{n}[(x_1^2 + x_2^2 + ... + x_{100}^2) - n\bar{x}^2]$ ($n = 100$, x is the estimated error for each epoch, $\bar{x}$ is the average error of 100 epochs' estimated error). Smaller variance value has more stable estimation error between different epochs.

C. Studying Method Analysis

The theorem 1 shows that with high probability (w.h.p.), the number of nodes in CKN$_k$ (it is the set of waking nodes and outputted by the CKN algorithm for a given k) is within a logarithmic factor of the number of nodes in OPT$_k$ (it is the set of waking nodes and outputted by an optimal algorithm which can find a minimum connected k-neighborhood). This theorem is based on the radio range irregularity model.

Theorem 1. *For any $k \geq 1$, suppose n nodes are placed uniformly at random within a deployment area such that the average number of neighbors per node (assuming the radio-range-irregularity communication model) is $\geq 4(k + lnn)$. Then, with high probability, $|CKN_k| \leq \varepsilon 8cln^n \cdot |OPT_k|$ (c is a constant).*

Proof: Let G be the communication graph of all the nodes. By Chernoff bounds, all nodes in G have degree between $\frac{d}{4}(\frac{d}{4} \geq k + ln^n)$ and $4d$, w.h.p. (if we only focus on a w.h.p. result, the scenarios where some node has fewer than $d/4$ neighbors or more than $4d$ neighbors can be ignored).

The $|OPT_k|$ is the optimal number of neighbors. If we use the optimal sleep scheduling algorithm, and let G' be the graph induced from G by removing all the edges between sleeping nodes and each node in G' is required to have at least k neighbors, so the total number of edges in G' is $\geq nk/2$. Moreover, because each node in G' has at most $4d$ neighbors, the total number of edges in G' is less than or equal to $4d \cdot |OPT_k|$. Hence, we can get: $4d \cdot |OPT_k| \geq nk/2$, i.e., $|OPT_k| \geq \frac{nk}{8d}$.

If we use the CKN sleep scheduling algorithm, according to the CKN algorithm's description, $rank_t$ is the t'th smallest random number which is selected by a node in G. In CKN algorithm, all nodes with $rank_s > rank_t$ can go to sleep, and because there are at most t nodes with $rank_s \leq rank_t$, we can get: $|CKN_k| \leq t$ (w.h.p.). And without loss of generality, let $t = (cknln^n)/d$ and c is a constant.

We have that $\frac{|CKN_k|}{8cln^n} \leq \frac{kn}{8d} \leq |OPT_k|$, so $|CKN_k| \leq 8cln^n|OPT_k|$. If we consider the irregular radio range, the result becomes: $|CKN_k| \leq \varepsilon 8cln^n|OPT_k|$ w.h.p., where ε is attenuation factor. ■

V. Simulation Experiment and Observation Results

Our simulation will be based on this network: each node is duty-cycled (nodes need time to sleep in order to save energy, that is to say, they are sleep-scheduling) and every node's radio range is irregular (we use the DOI to implement the radio range irregularity of node). Moreover, our simulation is based on the NetTopo simulator [13].

A. Simulation Experiment Setup

Our WSN is deployed with 500 sensor nodes and the network size is $[500(length) \times 500(width)]m^2$. Moreover, we use 100 different seeds to generate 100 different topological structures (the topology of CKN algorithm is variational in different epochs, because of sleep scheduling).

Along with the dynamical changing of network's topology, the HCRL localization algorithm displays its performance based on the variety of different parameter settings. In this paper, we will investigate these parameters' relationships for measuring the localization error of algorithm: anchor node density, k, and DOI.

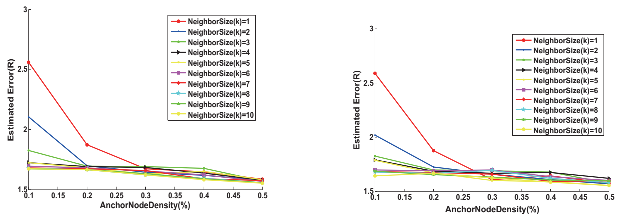
B. Simulation Results Observation and Analysis

Firstly, in our experiments, we set different values of k from 1 to 10 (each time increasing 1), the values of DOI from 0 to 0.7 (each time increasing 0.1) and the anchor node density is varied as: $10\%, 20\%, 30\%, 40\%$ and 50%. For a k value and anchor node density, each node runs 100 epochs in NetTopo simulator and all unknown nodes calculate the 100 epochs' average estimated error.

Fig. [3-6] show the estimated error with different k values, anchor node densities and DOI values.

From these experiments, we can find that the average estimation error with 100 epochs is reduced along with the increasing of k and anchor node density. Moreover, if the DOI value raises, the estimated error will be increased. We analyze the experimental results in detail, and can find three important points at least: (i) when DOI is invariable (e.g., DOI$= 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7$), with the increasing of k's value, the overall trend of estimation error is decreasing; (ii) increasing the anchor node density (when the anchor density is smaller than about 30%) sharply brings down the estimation error; (iii) the estimation accuracy increases dramatically as the anchor node density increases to 40% for all k and DOI values. However, after that, continuing to increase the anchor node density only slightly increases localization accuracy. In accordance with the experimental results of Fig. [3-6], for HCRL algorithm, in order to get a good average estimation error, we suggest that the neighborhood size (k) and the anchor node density used in duty-cycled and radio range irregular network, are: $k = 7$ and the anchor node density 40% and we argue that it is not quite cost-effective to further increase anchor node density for better accuracy after these phase transition points. And these conclusions can be used to set the anchor node density and the value of k saving energy without losing the accuracy of localization. Furthermore, from the experimental results: we consider the impact of radio range irregularity which affects the connectivity of nodes. Along with the parameter DOI changes from 0.0 to 0.7, the estimated error increases. So the k, DOI, anchor node density and estimation error are interactional.

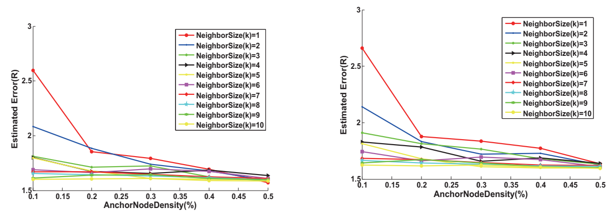
Secondly, in order to show the estimated error's stability in 100 epochs, we conduct a large number of experiments



(a) The estimated error when $k = 1-10$, five different types anchor node densities and $DOI = 0.0$

(b) The estimated error when $k = 1-10$, five different types anchor node densities and $DOI = 0.1$

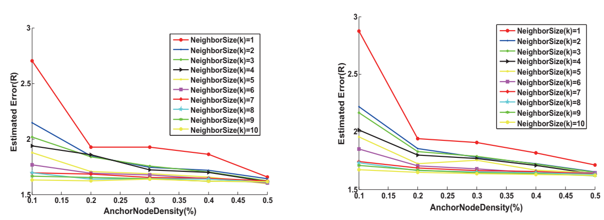
Fig. 3. The estimated error when $k = 1-10$, $DOI = 0.0, 0.1$ in different anchor node densities



(a) The estimated error when $k = 1-10$, five different types anchor node densities and $DOI = 0.2$

(b) The estimated error when $k = 1-10$, five different types anchor node densities and $DOI = 0.3$

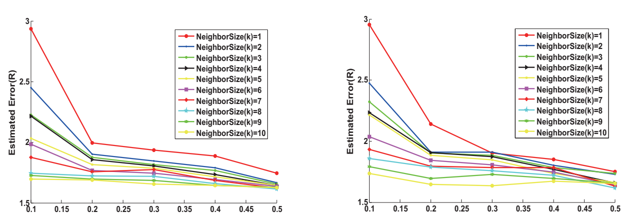
Fig. 4. The estimated error when $k = 1-10$, $DOI = 0.2, 0.3$ in different anchor node densities



(a) The estimated error when $k = 1-10$, five different types anchor node densities and $DOI = 0.4$

(b) The estimated error when $k = 1-10$, five different types anchor node densities and $DOI = 0.5$

Fig. 5. The estimated error when $k = 1-10$, $DOI = 0.4, 0.5$ in different anchor node densities

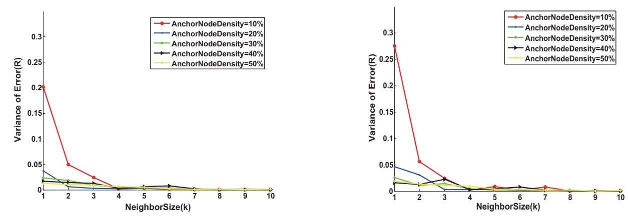


(a) The estimated error when $k = 1-10$, five different types anchor node densities and $DOI = 0.6$

(b) The estimated error when $k = 1-10$, five different types anchor node densities and $DOI = 0.7$

Fig. 6. The estimated error when $k = 1-10$, $DOI = 0.6, 0.7$ in different anchor node densities

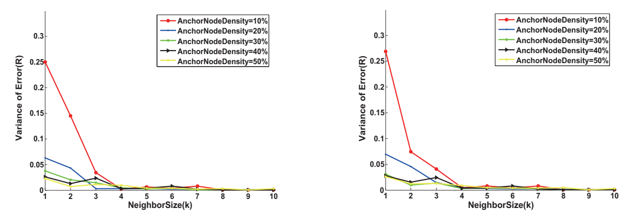
measuring the variance of average estimated error. The Fig. [7-10] show the variance of average estimated error with different k values, anchor node densities and DOI values.



(a) The variance of error when $k = 1-10$, five different types anchor node densities and $DOI = 0.0$

(b) The variance of error when $k = 1-10$, five different types anchor node densities and $DOI = 0.1$

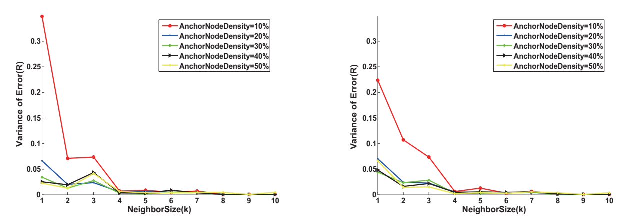
Fig. 7. The variance of error when $k = 1-10$, $DOI = 0.0, 0.1$ in different anchor node densities



(a) The variance of error when $k = 1-10$, five different types anchor node densities and $DOI = 0.2$

(b) The variance of error when $k = 1-10$, five different types anchor node densities and $DOI = 0.3$

Fig. 8. The variance of error when $k = 1-10$, $DOI = 0.2, 0.3$ in different anchor node densities

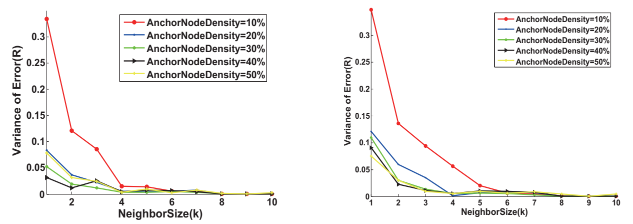


(a) The variance of error when $k = 1-10$, five different types anchor node densities and $DOI = 0.4$

(b) The variance of error when $k = 1-10$, five different types anchor node densities and $DOI = 0.5$

Fig. 9. The variance of error when $k = 1-10$, $DOI = 0.4, 0.5$ in different anchor node densities

From experiment results, first, we can find that the average estimated error for 100 epochs becomes more and more stable along with the increasing of k and anchor node density. Second, different DOI values have different stability, for k from 1 to 10 (each time increasing 1) and anchor node density from 10% to 50% (each time increasing 10%). E.g., when DOI$= 0.0$, the variance of error varies between 0.001 and 0.2 for 10 different k values, but when DOI$= 0.1$, the stability is worse for different k values and anchor node densities. For different k values, if the k value increases, more neighbors of a node are awake; that is to say, the probability that a node



(a) The variance of error when $k = 1 - 10$, five different types anchor node densities and $DOI = 0.6$

(b) The variance of error when $k = 1-10$, five different types anchor node densities and $DOI = 0.7$

Fig. 10. The variance of error when $k = 1 - 10$, $DOI = 0.6, 0.7$ in different anchor node densities

keeps awake for different epochs is increased, so the variance of average estimated error is decreasing (more stable).

VI. Conclusion

In this paper, we have formally analyzed the accuracy of HCRL algorithm (it belongs to DV-based localization algorithms) over duty-cycled and radio range irregular nodes. Based on the experimental investigation results, we have provided analysis about how the three parameters, k, DOI and anchor node density, affect the positioning accuracy and how the interaction between these three parameters. Through extensive simulation, we have shown an important fact that when $k = 7$ the estimated error of HCRL algorithm is stable between different epochs and the accuracy of localization is good for some DOI values and anchor node densities. Because these results of the analysis in this paper can be used as a direction for designing new improved algorithm and further research, future work includes designing a novel localization algorithm in real deployments with duty-cycled and radio range irregular nodes for improving the localization accuracy.

Acknowledgment

Lei Shu's research in this paper was supported by Grant-in-Aid for Scientific Research (S)(21220002) of the Ministry of Education, Culture, Sports, Science and Technology, Japan.

This work is partially supported by Natural Science Foundation of China under Grant No. 61070181.

Appendix

The algorithm 1 guarantees that every node has at least k waking neighbors, and it is called CKN algorithm.

Algorithm 1 The CKN sleep scheduling algorithm and run the following at each node s

1: Pick a random rank $rank_s$ for each sensor node;
2: Broadcast $rank_s$ and receive the ranks of its currently waking neighbors N_s.
3: If $|N_s| < k$ or $|N_v| < k$ for any $v \in N_s$, remain awake. Return.
4: Compute $C_s = \{v | v \in N_s$ and $rank_v < rank_s\}$
5: A node s can go to sleep if any two nodes in C_s are connected either directly themselves or indirectly through nodes within node s's 2-hop neighborhood that have rank less than $rank_s$; and any node in N_s has at least k neighbors from C_s. Otherwise node s remains awake.
6: Return.

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