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Pulse-Based Distance Accumulation Localization Algorithm for Wireless Nanosensor Networks

LINA ZHOU, GUANGJIE HAN, (Member, IEEE), AND LI LIU
Department of Information and Communication Systems, Hohai University, Changzhou 213022, China

Corresponding author: Guangjie Han (hanguangjie@gmail.com)

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ABSTRACT Wireless nanosensor networks (WNSNs) consist of nano-sized communication devices, which are equipped with nano-transceivers, nano-antennas, and other functional modules. A nanosensor is an integrated device that ranges from 10 to 100 μm^2 in size. Due to the limited communication capabilities of WNSNs, existing localization algorithms and protocols for wireless sensor networks (WSNs) are no longer applicable to WNSNs. This paper proposes a pulse-based distance accumulation (PBDA) localization algorithm for WNSNs that can be utilized to estimate the distance between nodes with known positions and nodes with unknown positions. The algorithm adopts femtosecond-long pulse for terahertz band communication based on ON–OFF keying (OOK) modulation. A clustering algorithm is first employed to reduce the energy consumption and time delay, then the nano-device analyzes the value of the received pulse based on the OOK modulation and estimates the distance between nodes. MATLAB simulations are implemented to verify the performance of PBDA by comparing it against the flooding-based hop-counting algorithm and cluster based hop-counting algorithm in terms of estimated distance accuracy, energy consumption, and time delay. The trilateral positioning method is also utilized to compare the localization error of PBDA with that of distance vector (DV)-hop. The results show that PBDA is able to support WNSNs with very high density in ranging and locating.

INDEX TERMS Wireless nanosensor networks (WNSNs), on-off keying (OOK) modulation, femtosecond-long pulse, pulse-based distance accumulation (PBDA).

I. INTRODUCTION

A. BACKGROUND

Rapid advancements in microelectronic have made nanotechnology very popular and nanotechnology spurred the development of wireless communications [1]. Nanoscale devices can provide remarkable technological solutions in a variety of fields, especially the biological, industrial, military, and food security fields [2]–[5]. New nanomaterials and nanoparticles at the microcosmic level exhibit unique properties opposed to those of the macro level. The purpose of nanotechnology is not only in developing ultra-miniaturized classical machines, but also taking advantage of the unique characteristics of nanomachines and realizing new functionality leading to innovative applications. For example, a nanosensor can detect chemical compounds or viral agents in concentrations as low as one part per billion.

Wireless sensor networks (WSNs) are, to date, relatively sophisticated; researchers have generally shifted their focus to wireless nanosensor networks (WNSNs) [6]. Although a single nanosensor can detect accurate event data, it is subject to limited transmission distance (less than 1*m*). Information interactions among multiple nanosensors can expand the communication capability of the single nanosensor, to this effect, allowing WNSNs to execute more complex tasks; nanosensors are able to share information and cooperate with each other in a multi-hop fashion.

WNSNs consist of nano-sized communication devices which are equipped with nano-transceivers, nano-antennas, and other functional modules. The internal abstract architecture of a nanosensor device is shown in Fig. 1. A nanosensor is an integrated device ranging from 10 to 100 μm^2 in size. The nano-antenna should be manufactured down to a few hundreds of nanometers to work on extremely high operating frequency bands (0.1∼10.0 terahertz (THz)). Nanosensor nodes can effectively realize network communication and information sharing through femtosecond-long pulses in the THz band.

Infrared, GPS, and ultrasonic ranging technologies require additional hardware. Considering the characteristics of nanodevices, including extremely small size, limited energy,

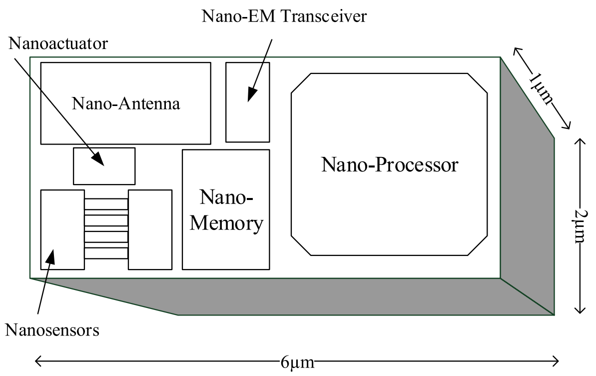


FIGURE 1. An integrated nanosensor device.

limited communication capability [7], it is effectually impossible to equip them with additional ranging hardware. Most ranging techniques in WSNs use carrier-based communication schemes, as well, which are ineffective in WNSNs as nanoscale transceivers are unable to generate carrier signals. Consequently, pulse-based communication schemes are more feasible due to the extremely high speed communication system in WNSNs. Existing traditional localization algorithms and protocols for WSNs are simply not suited to WNSNs.

B. CONTRIBUTION

This paper proposes a localization algorithm for WNSNs designed to improve their ranging accuracy while simultaneously truncating their average delay and reducing their energy consumption. Based on previous work by Tran-Dang *et al.* [8], we propose a more precise and practical solution to resolve he WNSN localization problem. The main contributions of this paper can be summarized as follows.

1) We propose a cluster establishment mechanism to reduce the energy consumption and average delay. A node becomes a cluster head in a circle if it has the largest residual energy; this extends the lifetime of the whole network.
2) Communication among nanosensor nodes is based on on-off keying (OOK) modulation to improve localization accuracy. The OOK modulation transmits a pulse to present a logic "1" and keeps silent to present a logic "0". In this case, incorporating the feature of WNSNs (encoding information by pulses), the receiver device equipped with nano-devices analyzes the value of the received pulse and estimates the distance between nodes.
3) As the low-energy nanosensor nodes cannot operate complicated protocol, we propose a PBDA localization algorithm consisting of four phases. Phase 1: Nodes are classified into three categories including corner nodes, border nodes, and center nodes, and nodes in the network communicate through peculiar packets. Phase 2: Clusters are developed and nodes with the most residual energy are chosen as the cluster heads. Phase 3: Packets are transmitted and forwarded via cluster heads. Phase 4: When packets are transmitted, the distance between the previous node and present node is accumulated, so the final distance is the distance from one side of the network to the other side.
4) To relax the requirement of accurate synchronization for detecting a very low energy pulse, we transmit multiple pulses in a burst rather than a single pulse. Channel conflict does not occur because the duty ratio of pulse is very small.

It is not clear whether anchor nodes yield their absolute positions via GPS [9] or other devices that can be deployed in WNSNs. If the network does not have anchor nodes, the node can only accomplish the ranging process. PBDA is a ranging method that can be used to accurately estimate the distance between two nodes. Nanosensors can communicate with each other and store significant information (e.g., RFID tags). They are integrated on the product at the beginning of the manufacturing process. One potential application of PBDA is to monitor the status (e.g., size, health) of intelligent products which are equipped with nanosensors during their life circle. The intelligence level of the product is revealed by the ability to monitor their dimensions or localizations continuously; these abilities can be implemented by WNSN ranging algorithms.

C. PAPER ORGANIZATION

The remainder of this paper is organized as follows. Section II, provides a review of the related work. In Section III, we introduce the THz band pulse-based system and construct the system model. Section IV presents the PBDA localization algorithm. Our simulation and numerical analysis results are presented in detail in Section V. Section VI concludes the paper and discusses future research directions.

II. RELATED WORK

A multitude of localization algorithms have been proposed for WSNs to date [10]. They can be roughly divided into range-free and range-based categories. The most well-known range-free algorithm is distance vector (DV)-Hop [11]. DV-Hop does not require any point-to-point distance or angle estimation. Its localization accuracy is dependent solely on the network connectivity quality. Range-based localization algorithms include angle of arrival (AoA) [12], time of arrival (ToA) [13], time difference on arrival (TDoA) [10], and received signal strength indicator (RSSI) [14]. Researchers focusing on WNSNs have extended the conventional localization algorithms specific to WSNs to the nanoscale.

DV-Hop was proposed by Niculescu and Nath [11], [12]. Anchors are equipped with GPS and broadcast their location information to all the nodes via a flooding mechanism. Nodes with unknown positions are located based on the hop counts from the anchors. DV-Hop relies on a dense and uniform network to enhance location precision; it is suitable for WNSNs in certain aspects as the network environment is in accordance with WSN characteristics. It remains to be seen whether anchors with GPS can be deployed in WNSNs, however.

AoA is an algorithm which estimates and maps relative angles between neighbor nodes to locate unknown nodes. Angle information is received from an omnidirectional antenna. The scheme is hardware-constrained, as it needs an array of RF antennas to locate nodes with unknown positions; it is not suitable for WNSNs.

ToA uses the signal propagation time to estimate the distance between nodes; expensive electronic devices are necessary to achieve precise time synchronization among different nodes. Low-power nanosensors can only perform simple tasks, but as mentioned above, nano-sized communication devices cannot be equipped with extra hardware. Therefore, ToA cannot be applied to node localization in WNSNs.

In TDoA, the distance between two communication nodes is measured based on the difference in propagation times of two radio or acoustic signals which are originally sent at an identical point. Similar to the ToA technique, TDoA needs extensive hardware and consumes excessive energy. These disadvantages of TDoA limit its application for localization in WNSNs.

RSSI measures the distance between two nodes by translating signal strength into distance estimates. Localizations based on RSSI are sensitive to channel models. RSSI also depends on carrier-based communication schemes which cannot be provided by WNSNs in THz channels, rendering it infeasible for WNSNs.

Jornet and Akyildiz [15] proposed a femtosecond-long pulse-based modulation for THz band communication in nanonetworks based on the transmission of 100-femtosecond-long pulses following an OOK modulation. The proposed technique can be applied to inter-node communication in WNSNs. Tran-Dang *et al.* [8] proposed two localization algorithms based on hop counting, namely, the flooding-based hop-counting (FBHC) algorithm and cluster based hop-counting (CBHC) algorithm for WNSNs. FBHC uses a flooding mechanism to broadcast packets to all nodes in the network and counts the number of hops between two boundaries of the network; CBHC introduces the concept of clusters on the basis of FBHC to classify all sensor nodes into different clusters. The number of hops is counted via an election and cooperation process in the cluster heads. Flooding packets are only passed forward through cluster heads, thus, CBHC reduces the energy consumption caused by duplication in the relay of broadcast packets. This prolongs the whole network life cycle.

To the best of our knowledge, the algorithms proposed by Hoa Tran-Dang *et al.* are the only schemes that currently exist for WNSN localization. In this study, we built an algorithm (PBDA) based on FBHC and CBHC to achieve more precise WNSN localization. In the proposed scheme, communications among nanosensor nodes are based on OOK modulation, packets are transmitted through pulses, and the distances between nodes are estimated by the value of the received pulse, which enhances the localization accuracy.

III. WIRELESS NANOSENSOR NETWORK ARCHITECTURES

A. COMMUNICATION MECHANISM FOR WIRELESS NANOSENSOR NETWORKS

1) POSSIBLE FREQUENCY BANDS FOR WNSNs

The THz band and the upper part of the megahertz band (100.0∼1000.0 MHz) are two potential operation frequency bands for WNSNs. The THz band can satisfy the communication requirement of modern nano-antennas [16], and the MHz band can be produced by an electromechanical nano-transceiver. The upper part of MHz has low frequency and nanosensor devices can communicate with each other over longer distances, however, the frequency efficiency of generating electromagnetic waves in MHz is predictably low [17], making it infeasible for nanosensor devices to operate in the MHz band; nanosensor devices can, though, potentially communicate with each other in the THz band.

2) INFORMATION ENCODING AND MODULATION

WNSNs require their own encoding mechanisms to fit the THz channel and provide ultra-high frequency communication. Per the limitations of nano-engineered hardware, the encoding mechanism must be feasible in certain applications. A femtosecond-long pulse can be achieved in a short period of time and remain stable in the THz channel [18]. The energy of the pulses is not reduced down to zero by the THz channel. The femtosecond-long pulse represents a notable advantage for energy-limited nanosensor devices due to its simplicity and low energy consumption. The traditional channel paradigm which uses a continuous wave can be replaced by a new modulation technology based on the femtosecond-long pulse for WNSNs.

Traditional pulse-based WSN information encoding mechanisms can be split into pulse amplitude modulation, pulse phase modulation, pulse frequency modulation, and pulse rate modulation categories [19]. These methods are not applicable for communication among nanometer sensor devices for a few reasons. First, the frequency of the THz spectrum is flexibly selective, thus transferring data into pulse shape is infeasible. Second, strict time synchronization among the nanometer sensor devices is required in the process of pulse phase modulation. In addition, the provided pulse width is fixed and must be retained in the THz spectrum. In short, traditional pulse modulation methods are not applicable for WNSNs. A novel approach is called for to implement information code modulation.

An interesting and potentially practicable information coding modulation is to conduct energy exploration to detect whether there are signals "1"of the pulses in the environment. The existence of a pulse represents a logic "1", or else a logic "0" is represented [20]. In order to detect these very small pulse energies, each nanosensor device must be equipped with a matched filter; precise time synchronization and sampling precision are also necessary. To relax this requirement, we assume that multiple pulses are transmitted in a burst at each time point rather than a single pulse.

Accordingly, individual pulse attenuation during the propagation process does not affect data reception at the receiver. Based on this information coding modulation, the duty ratio of the pulse is small and channel conflict can be avoided [18]. Thus, channel multiplexing can be realized without considering channel conflict. This enhances the information transmission efficiency of the whole network.

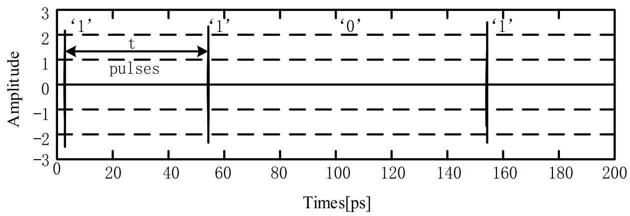


FIGURE 2. **On-Off keying (OOK) modulation.**

B. THZ BAND PULSE-BASED SYSTEM

In the system described in this paper, WNSNs adopt femtosecond-long pulses for THz band communication based on OOK modulation. As shown in Fig. 2, the OOK modulation transmits a femtosecond-long pulse to present a logic "1" and keeps silent to present a logic "0". Because range-based localization algorithms are not applicable in WNSNs, we focus on exploring an alternative, feasible localization algorithm. The signal at the receiver depends on the antenna impulse response in reception, so the distance between the receiver and transmitter can be estimated based on the analysis of the pulse value − then the distance between two communication nodes can be obtained. The energy-limited nanosensor device can transmit pulses with peaks of a few μW. The energy of the pulses can be converted to the aJ $(10^{-18}J)$ level. The signal received by a nanosensor device is given as follows: [15]

$$s_R^j(t) = \sum_{k=1}^{K} A_k^u(pt - kT_s - \tau^u) * h^{u,j}(t) + n_k^{u,j}(t) \quad (1)$$

where K is the number of symbols per packet, A_k^u refers to the amplitude of the kth symbol transmitted by the nanodevice (either 0 or 1), p denotes a pulse with duration T_p, T_s is the time between consecutive transmissions, τ^u is a random initial time, $h^{u,j}$ is the system impulse response between two devices, and $n_k^{u,j}$ is the noise during the transmission of the kth symbol. During the process of pulse propagation, the transmission distance increases as signal transmission time t increases. The relationship between the received signal $y(t)$ and the propagation distance is also described by Jornet and Akyildiz [15]. Analytical model and COMSOL simulations show that the voltage value at the receiver and the distance between nodes have qualitative relationships. We assume there is a mathematical relationship between distance and voltage:

$$D = f(E^p) \quad (2)$$

where E^p is the received voltage value at the receiver equipped with the nano-device and D is the distance between two communication nodes.

In the proposed scheme, data packets are transmitted through the pulse-based system and the distance between two nanosensor nodes can be estimated without any additional equipment.

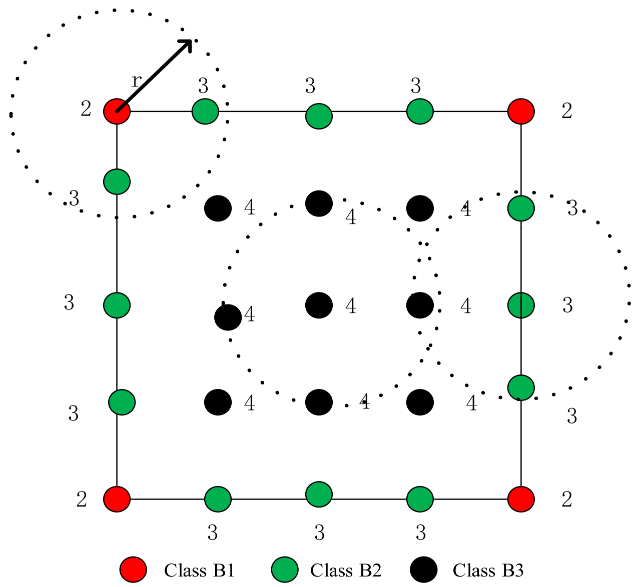


FIGURE 3. **Network structure model.**

C. SYSTEM MODEL

The network structure model is illustrated in Fig. 3. Nodes are randomly deployed in a square field. Due to the large-scale deployment feature of WNSNs, it is assumed that the nodes are uniformly deployed. There are N nodes in an $L \times L$ square area. We divide the nodes into three classes: Corner node B1, border node B2, and center node B3. The broken circles are the communication range of nodes. Center nodes have the most neighbor nodes, followed by border nodes; corner nodes have the fewest.

λ_0 is the density of nodes in area of L^2: $\lambda_0 = \frac{N}{L^2}$

λ_1 is the density of nodes in area of $\frac{1}{4}\pi r^2$: $\lambda_1 = \frac{1}{4}\pi\lambda_0 r^2$

λ_2 is the density of nodes in area of $\frac{1}{2}\pi r^2$: $\lambda_2 = \frac{1}{2}\pi\lambda_0 r^2$

Assume M_i is the density in the communication range of node N_i.

$$B1 = \{N_i || M_i \le \lambda_1, \quad i = \{1, \ldots, N\}\}$$
$$B2 = \{N_i || \lambda_1 < M_i \le \lambda_2, \quad i = \{1, \ldots, N\}\}$$
$$B3 = B \backslash (B1 \cup B2)$$

Per their classification, each node sends packets to detect its neighbors using a flooding mechanism. An example is shown in Fig. 3, where red nodes have two neighbor nodes (class B1) with the least density; green nodes belong to class B2 and black nodes belong to class B3.

IV. PULSE BASED DISTANCE ACCUMULATION (PBDA) ALGORITHM

The PBDA algorithm consists of four phases. The nodes are classified in the first phase; the second and third phases create clusters of B1 and B2 nodes and the fourth phase calculates the distance between two corner nodes based on flooding.

Phase 1: Packets are broadcast via flooding mechanism and classified according to neighbor discovery. Each node broadcasts a packet to calculate the number of neighbor nodes, then the quantity of neighbor nodes split them into classes by density. B1 nodes are subjected to the following steps. The pseudo code of Phase 1 is shown in **Algorithm 1**.

Phase 2: Clusters are established and the cluster heads of B1 nodes are identified. The B1 nodes generate and broadcast a clustering-broadcast packet (Fig. 4(a)) via flooding mechanism. Only B1 nodes can pass packets forward − packets are dropped if they are received by B2 or B3 nodes. The clustering-broadcast packet consists of four fields. The first is the *ID* of the B1 node which originally generated the clustering-broadcast packet [21]. Here, we assume that every node has a unique *ID*. The second field is the type of the node that transmits the packet. The third field is the residual energy of the node. In this phase, each B1 node chooses the optimal node which has the most residual energy to be the cluster head. The last field, *EDC*, is a code that checks the transmission error. Because PBDA is based on the transmission of 100-femtosecond-long pulses by an asymmetric OOK modulation, the high-bits "1" may be lost during the transmission process [22]. After receiving the clustering-broadcast packets, B1 nodes choose the node with the highest

Algorithm 1 Determine the Types of Nodes

procedure Determine the types of node N_i (L, N_i, r, T_b)
  All nodes generate and transmit their beacon packets in the interval time T_b;
  Node N_i receives and counts the number of packets M_i;
  Node N_i calculates λ_0, λ_1 and λ_2;
  if $M_i < \lambda_1$ **then**
    Node N_i belongs to B_1 nodes;
  else
    if $\lambda_1 < \lambda_2 \leq \lambda_2$ **then**
      Node N_i belongs to B_2 nodes;
    else
      Node N_i belongs to B_3 nodes;
    end if
  end if
end procedure

TxID	Node Type of Tx	Residual Energy	EDC

(a)

TxID	Node Type of Tx	RxID	EDC

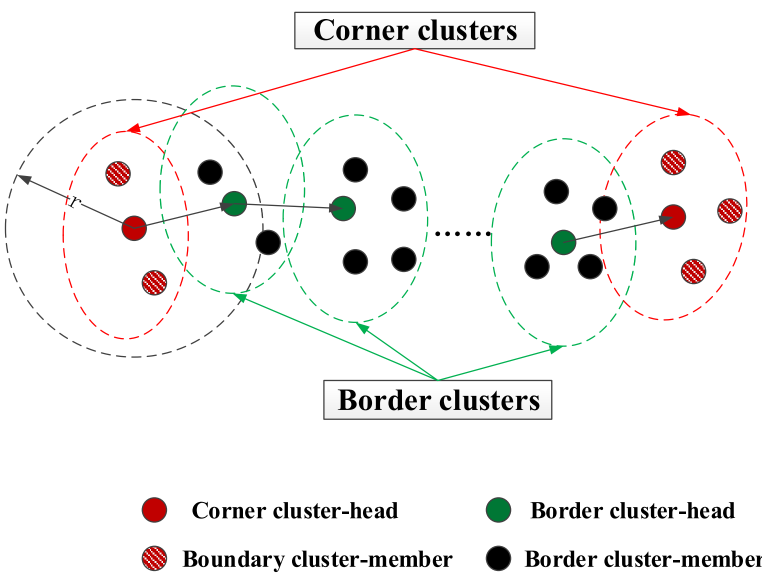
(b)

TxID	Node Type of Tx	Confirm Code	EDC

(c)

TxID	Node Type of Tx	Node Type of Rx	DIS	EDC

(d)



(e)

FIGURE 4. Packets in PBDA. (a) Clustering-broadcast packet; (b) Clustering-reply packet; (c) Notify packet; (d) Flooding packet; (e) Cluster creating process.

residual energy as the cluster head. B1 nodes then join the cluster by replying a clustering-reply packet (Fig. 4 (b)) to inform the cluster head. i.e., B1 nodes with lower residual energy send clustering-reply packets to CH, which has the highest residual energy. The clustering-reply packet consists of four fields. The *RXID* field represents the *ID* of the node which should receive the packet, that is, the *ID* of the cluster head.

Phase 3: Clusters are established and cluster heads of B2 nodes are chosen. The process is similar with the second phase. After receiving the clustering-reply packet, the cluster nodes continue to send the notify packet (Fig. 4(c)). The confirm code is delivered to B2 nodes, informing them to create clusters and choose cluster heads through clustering-broadcast and clustering-reply packets. When B3 nodes receive the packets, they discard them. An example of the cluster establishment process is shown in Fig. 4(e). All the nodes are grouped in clusters in this manner. Each cluster includes only one type of node and one cluster head. Certain packets are originally generated by B1 nodes, as well. These packets are transmitted to other B1 nodes on the other side of the network via B2 nodes. The pseudo code of Phases 2 and 3 is given in **Algorithm 2**.

Phase 4: Flooding packets are forwarded (Fig. 4(d)) through the cluster heads and the distance between the corner nodes is calculated. The third field represents the types of the nodes that only receive the packet and prepare to pass it forward. The *DIS* field reserves the cumulative distance from the original B1 node to the current node; this field is initially set to ''0''. Each time the flooding packet is transmitted, the *DIS* value increases. $DIS = DIS + r'$, where r' is the distance between the previous node and the current node. (The calculation process of this value is described above.) Flooding packets continue forwarding through B2 node clusters until they reach the B2 nodes on the other side of the network. The ultimate value of *DIS* is the estimated distance from one side of the network to the other side. The pseudo code of this step is given in **Algorithm 3**.

Algorithm 2 Create Clusters and Select CHs

```
procedure Create Clusters and Select CHs (B1, B2, B3)
    Only B1 nodes broadcast clustering-broadcasting packets (Node Type of Tx=00);
    if Other B1 nodes receive these packets then
        Compare residual energy of nodes. Nodes with lower residual energy send clustering-reply packets to CH which has the highest residual energy;
    else
        if B2 and B3 nodes receive these packets then
            Discard the packets;
        end if
    end if
    CHs of B1 nodes broadcast the notify packets;
    if B2 nodes receive the notify packets then
        These B2 nodes broadcast their clustering-broadcast packets (Node Type of Tx=01);
    else
        if B2 nodes receive these packets then
            Go to step 4;
        else
            if B1 and B3 nodes receive these packets then
                Discard them;
            end if
        end if
    end if
    repeat
        CHs of B1 nodes broadcast the notify packets;
        if B2 nodes receive the notify packets then
            These B2 nodes broadcast their clustering-broadcast packets (Node Type of Tx=01);
        else
            if B2 nodes receive these packets then
                Go to step 4;
            else
                if B1 and B3 nodes receive these packets then
                    Discard them;
                end if
            end if
        end if
    until all B1 nodes and B2 nodes join the clusters;
end procedure
```

V. SIMULATION

Simulations were performed in Matlab to demonstrate the effectiveness of PBDA. The performance of PBDA was compared against FBHC, CBHC, and Dv-Hop. A series of performance metrics (e.g., ranging accuracy, average delay, residual energy) were used to evaluate the performance of PBDA in WNSNs. The triangular positioning method was then introduced to evaluate the localization errors of FBHC, CBHC, PBDA, and Dv-Hop. The performance of PBDA was then compared to Dv-Hop by varying the amount of unknown nodes and anchor nodes.

A. PERFORMANCE EVALUATION METRICS

In traditional sensor network localization algorithms, the major factors that affect network performance include node density, target density, communication radius, monitoring areas, and others. Generally, localization algorithm performance is evaluated according to localization error, energy consumption, and average delay parameters.

1) LOCALIZATION ERROR

Node localization error directly reflects the accuracy of the localization algorithm and can be calculated as follows:

$$L_E = \frac{\sum_{i=1}^{N-M} \sqrt{(x_i{'} - x_i)^2 + (y_i{'} - y_i)^2}}{R \times (N - M)} \tag{3}$$

Algorithm 3 Estimate the Distance Between Two Nodes Based on PBDA Algorithm

procedure Estimate the Distance ($B1$, $B2$, $B3$, DIS, T_b, E^p)
  B1 nodes broadcast their flooding packets (Node Type of Tx=00, DIS=0);
  repeat
    if CHs of B2 nodes receive the flooding packets **then**
      Create new flooding packets and broadcast them (Node type of Tx=01, Node Type of Rx=01);
      $r = f(E^p)$;
      $DIS = DIS + r$
    else
      if Cluster members receive these packets **then**
        Discard them;
        Cluster members with the second highest residual energy will be active in the next round;
      else
        if B3 nodes receive these packets **then**
          Discard them;
        end if
      end if
    end if
  until CH of B1 nodes at the other side receives the flooding packet;
  CH of B1 node calculates the distance (final DIS);
end procedure

where (x_i, y_i) donates the estimate node coordinates of the algorithm, $(x_i{}', y_i{}')$ stands for the real coordinates of the node, R refers to the communication radius, N is the number of nodes and M is the number of anchor nodes [23].

2) ENERGY CONSUMPTION

The average energy consumption refers to the total energy consumption of all nodes in the network divided by the total number of nodes. Because sensor nodes are typically powered by battery, an important issue related to localization is improving localization accuracy with minimal energy consumption. The average energy consumption in the network is expressed as follows:

$$AverConsumption = \frac{E_{consume}}{Nodes} = \frac{E_{sense} + E_{trans}}{Nodes} \tag{4}$$

Here, the packets are transmitted mainly through a forward pass when the sensor node detects the event, so the main consideration of the energy consumption is E_{trans}.

Average delay: This factor represents the time it takes for a packet to be transmitted from one end of the network to the other end. The average delay of the localization algorithm not only directly affects the network life cycle and its precision, but also indirectly reflects the overall efficiency of the algorithm. Generally, the average delay equals the sum of the sending, transmission, processing, and queuing delays. Because the THz spectrum information transmission time is very short, we only consider sending and processing delays here.

B. SIMULATION SETUP

Relevant simulation parameters are outlined below.

- Nanosensor nodes are randomly deployed;
- Network topology is isotropic;
- Region is assumed to be a square area of fixed size 100 cm × 100 cm;
- Nanosensor nodes only communicate with neighbor nodes in THz band range;
- The transmission radius is 1cm and each node has the identical communication range;
- When varying the number of unknown nodes, the proportion of the anchor node is maintained at 20%;
- When varying the number of anchor nodes, the total number of nodes in the network is 1000.

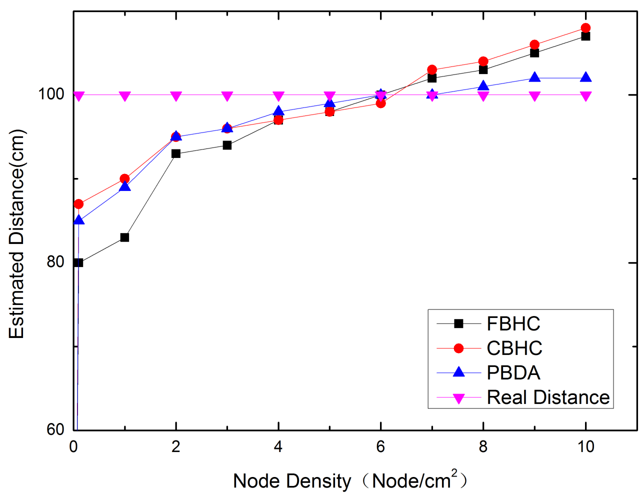


FIGURE 5. Estimated distance.

C. SIMULATION RESULTS AND ANALYSIS

1) ESTIMATED DISTANCE

Fig. 5 depicts the relationship between node density and the estimated distance from one side of the network to the other side. When the node density is relatively low (less than $2Node/cm^2$), the localization errors of FBHC, CBHC, and PBDA are large. The node communication range is 1 cm. When the number of nodes per square centimeter is less than $2Node/cm^2$, the entire network connectivity is too poor to achieve direct communication among nodes. As a result, the number of hops is smaller than the actual number of hops. When the node density is greater than $2Node/cm^2$, the connectivity of the entire network can be realized and the packet can be transmitted from one side of the network to the other side.

In the random deployment scheme, even with uniform density, there is still a possibility that some nodes cannot communicate with each other. When the density of the nodes reaches $6Node/cm^2$), the network has the highest accuracy possible; at this point, there is full connectivity (both direct and indirect) between any two nodes. When the node density is greater than $6Node/cm^2$), the estimated distance is longer than the actual value (100 cm) because the increased node density causes the packet forwarding process to be repeated through the same type of node (B2), yielding excessive hop count and localization error.

When the node density increases to a certain extent, the estimated distances of all three algorithms grow longer than the actual values due to the inaccurate number of hops. Among FBHC, CBHC, and PBDA, FBHC has the maximum localization error as it has the largest packet forwarding number. In addition to the inaccurate number of hops, simply using the value as the distance of each hop is a major factor of error. PBDA effectively reduced this part of the error and exhibited higher ranging accuracy as the node density increased.

In terms of range accuracy, we determined the impact of the node density to evaluate these three algorithms. The simulation results show that PBDA outperforms CBHC and FBHC.

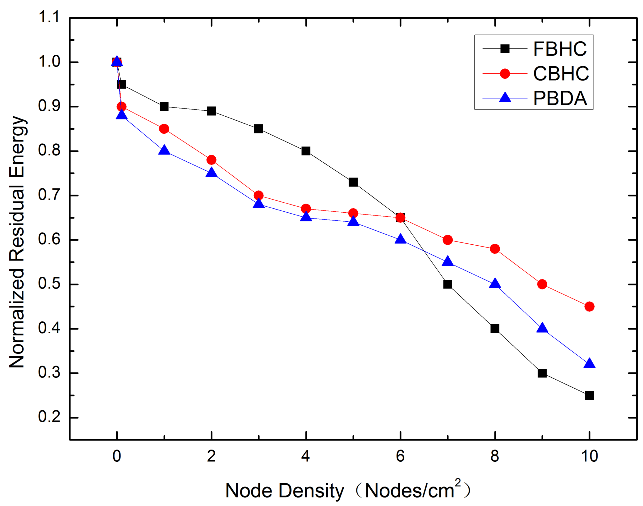


FIGURE 6. Energy consumption.

2) ENERGY CONSUMPTION

The energy consumption shown in Fig. 6 is a function of the node density. As the node density increases, the average residual energy of each algorithm shows a different degree of decline. The process through which nodes receive and transmit packets consume greater amounts of energy as node density increases, as well. When the node density is less than $2Node/cm^2$), FBHC achieves the minimum energy consumption. Because the node density is small, even if the packets are transmitted through flooding, the process efficiently utilizes energy. For CBHC and PBDA, with a small number of nodes, cluster heads also need time to accumulate distance hop-by-hop during clustering and more energy is consumed.

As the node density increases, although CBHC and PBDA consume more energy than FBHC, they significantly reduce the gap. Once the density reaches $6Node/cm^2$), however, CBHC and FBHC are almost the same as FBHC in terms of energy consumption. In effect, introducing the cluster grouping process does significantly optimize the energy consumption. Conversely, because FBHC repeats the flooding process to forward the packet, it wastes energy. PBDA includes pulse ranging, so the cumulative distance process is another non-negligible part of energy consumption. When the node density is larger than $6Node/cm^2$), the FBHC algorithm no longer has this advantage as overlapping and implosion problems related to the flooding mechanism appear at larger node densities. Each B2 node consumes considerable energy, while a useful path for packet transmission consumes only a small amount of energy.

In summary, CBHC and PBDA have higher node density than the other schemes we tested, which is conducive to extending the network lifetime.

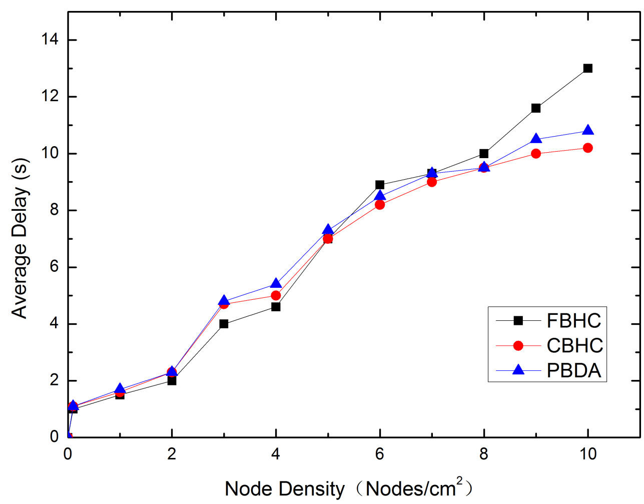


FIGURE 7. Average delay.

3) AVERAGE DELAY

Fig. 7 shows the average delay as a function of node density for different algorithms. The three algorithms show similar energy consumption in terms of average delay as the node density (i.e., neighbor node quantity) increases. The communication radius remains unchanged, so the process of flooding broadcast nodes or creating clusters takes time. We also found that when the node density is less than $5Node/cm^2$), CBHC and PBDA have a larger delay than that of FBHC. This is because when the node density is small, simply flooding the broadcast nodes is inappropriate while CBHC and PBDA undergo an additional clustering process. Distance calculation causes a processing delay in PBDA, but the delay is tolerable compared to the transmission delay of flooding. Overall, PBDA outperforms the other algorithms in a high node density environment.

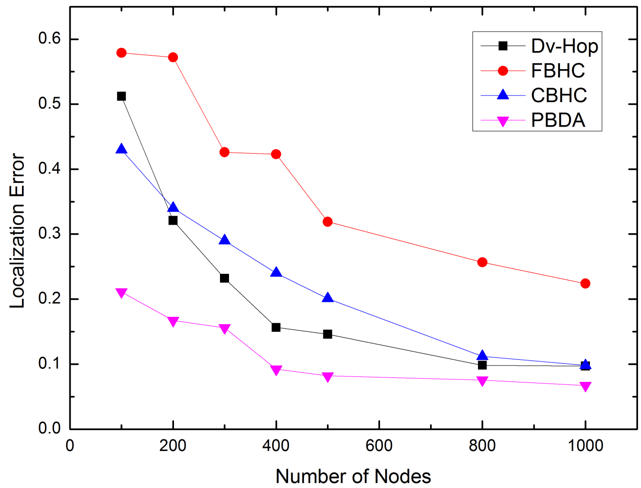


FIGURE 8. **Localization error as a function of the number of nodes.**

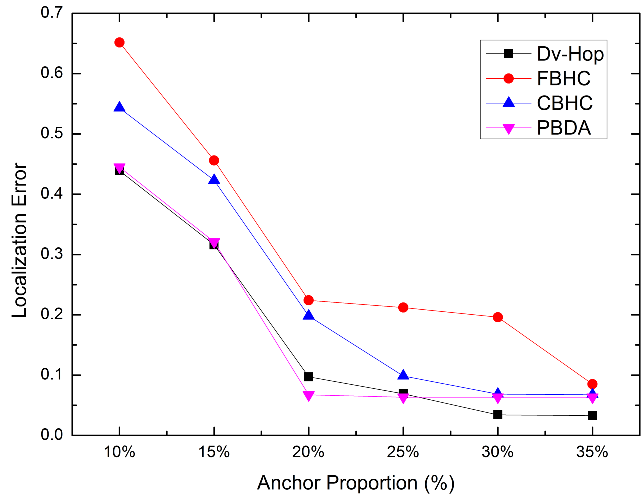


FIGURE 9. **Localization error as a function of anchor proportion.**

4) EFFECT OF THE NUMBER OF NODES ON LOCALIZATION ERROR

As shown in Fig. 8, as the number of nodes increases, the localization errors of the four algorithms show varying degrees of decrease. This occurs because the node connectivity of the network increases and thereby the localization accuracy is improved. For Dv-Hop, the main factor of localization error is that the shortest path between any node and the anchor node is a straight line; the number of anchor nodes also has a direct relationship with the localization accuracy, so when the number of anchor nodes is 20% of all nodes, localization tends to stabilize once node density reaches a certain level.

For hop-counting-based localization algorithms FBHC and CBHC, the localization error results mainly from the number of hops. The measured distance between nodes and anchor nodes is larger than the true value. For PBDA, using the pulse value to calculate the distance between two nodes significantly improves the localization accuracy. When the anchor nodes comprise a constant proportion of the entire network, the advantages of PBDA grow more obvious as the node density increases.

5) EFFECT OF THE NUMBER OF ANCHOR NODES ON LOCALIZATION ERROR

The localization errors of Dv-Hop, PBDA, and the two hop-counting-based algorithms FBHC and CBHC are shown in Fig. 9 as a function of anchor proportion. When the anchor node proportion is less than 20%, all four algorithms show a large localization error. This is because when the number of anchor nodes is small, nodes can only select anchor nodes which are far away from them. For Dv-Hop, the fewer the anchor nodes, the larger the accumulated error. For FBHC and CBHC, the main source of error is the average distance of each hop, i.e., the communication radius. For PBDA, the localization error is caused by the process of converting the pulse signal into distance, where the estimated value is not accurate (as expected). This is also related to the physical properties of the manufactured equipment.

When the proportion of anchor nodes exceeds 20%, Dv-Hop performs better in terms of lower localization error compared to the other three algorithms. When the anchor node density is relatively large, an unknown node can choose the nearest anchor nodes to locate. The estimated hop-distance is closer to the real distance between two sensor nodes, thus the localization error is reduced. Although the localization error of FBHC, CBHC, and PBDA is alleviated when the anchor nodes exceed 20%, the accumulated error of hops cannot be eliminated. Especially for PBDA, increasing the number of anchor nodes actually necessitates an additional calculation.

6) SUMMARY OF SIMULATION RESULTS

According to simulation results, there is no particular algorithm that outperforms the other consistently across all scenarios. Based on the energy efficiency technology and certain application environments, different algorithms have unique advantages. Below, we summarize the characteristics of the four algorithms (FBHC, CBHC, Dv-Hop, and PBDA) and analyze the optimal application scenario for each.

To the best of our knowledge, FBHC was the first localization algorithm specific to WNSNs. FBHC is simple and consumes energy only through the packet forwarding process. When the network node density is small, FBHC is superior in regards to energy savings.

CBHC is based on FBHC and was modified to provide performance improvements. Because transmitting packets by flooding would cause implosion and overlapping problems at elevated node density, CBHC is improved based on the cluster establishment process. Cluster heads are responsible for data forwarding, which not only decreases the energy consumption but also improves the algorithm's efficiency. Therefore, CBHC is suitable for WNSN scenarios with high node density.

Although FBHC and CBHC are feasible methods to realize a rough estimate of the distance between two nodes, the localization error is rather large. The shortest path between two nodes is considered a straight line, which results in an estimated distance larger than the real distance; further, during the packet forwarding process, the distance of each hop is calculated as the radius of communication range "r" and further increases the error.

PBDA takes advantage of clustering to save energy. The WNSN, as discussed above, is a novel network model which has high node density. Considering the information coding modulation of WNSNs, PBDA calculates the hop distance according to the pulse value received at the receiver equipped with nanosensor devices. PBDA thus shows enhanced ranging accuracy at low energy consumption compared to the other algorithms. PBDA is suitable for applications in which nodes are deployed at high density and high accuracy localization is required.

Dv-Hop is the most classic range-free localization algorithm for WSNs. Its advantage is its simplicity compared to other localization techniques; it does not depend on range measurement error. The drawbacks of Dv-Hop are that it can only work for isotropic networks in which localization algorithms based on distance are appropriate. Dv-hop also needs anchor nodes, because trilateration uses ranges based on a minimum of four landmarks to find the coordinates of unknown nodes. The position information of the landmarks is received from GPS equipment. GPS, which is a public service, can satisfy some of the requirements in WSNs to help locate anchor nodes in the network. Attaching a GPS receiver to each node is not always the preferred solution, however, for several reasons (e.g., cost, limited power, inaccessibility, imprecision, form factor). GPS localization also introduces error that is nonnegligible in WNSNs considering the extremely small size of the network environment. To this effect, it is impractical for WNSNs to have nanosensors equipped with GPS. Whether anchors with known positions can be deployed in WNSNs remains an open problem, the solution to which is strongly dependent on the industrial manufacturing of GPS equipment.

It is also important to note that anchors cannot be deployed in WNSNs under any currently available technique. The distance between two nanosensor nodes can be estimated effectively, but the application scope is limited.

VI. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

The localization technology used in traditional WSNs is not suitable for WNSNs due to their specific THz communication paradigm. This paper proposes a novel PBDA localization algorithm for WNSNs that is advantageous in terms of estimated distance and energy consumption. It can be used as the basis of a range-free localization algorithm and applied to similar environments.

In PBDA, nanosensor nodes are divided into three types (corner nodes, border nodes, and center nodes) in a square area. Each time packets are transmitted hop-by-hop, the distance between two nodes can be calculated by accumulating the length of the total hop between them. Although the simulation model and the planar hypothesis are very simple, PBDA is theoretically efficient in obtaining ranging accuracy and prolonging the network's lifetime. It can be used as the basis of range-free localization algorithms and applied to similar environments.

Despite the fact that the algorithm can be simulated under certain conditions (limited network coverage, low memory, and processing ability) in WNSNs, practical feasibility analysis has yet to be taken into account. During exploration of future WNSN localization algorithms, attention should be given to different network environments (e.g., randomly deployed nodes, gridly, isotropic, anisotropy, C-type, L-type) [24]. Future work includes further analysis of the communication in the nanonetwork and the development of protocols to support a more effective WNSN.

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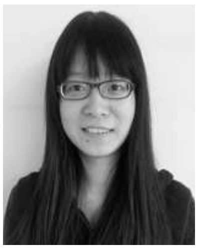
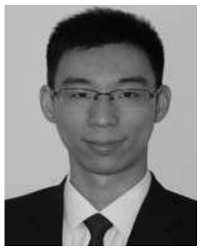
GUANGJIE HAN (S'03–M'05) received the Ph.D. degree from Northeastern University, Shenyang, China, in 2004. From 2004 to 2006, he was a Product Manager with ZTE Company. In 2008, he was a Post-Doctoral Researcher with the Department of Computer Science, Chonnam National University, Gwangju, South Korea. From 2010 to 2011, he was a Visiting Research Scholar with Osaka University, Suita, Japan. He is currently a Professor with the Department of Information and Communication System, Hohai University, Changzhou, China. He is the author of over 240 papers published in related international conference proceedings and journals. He holds 100 patents. His current research interests include sensor networks, computer communications, mobile cloud computing, and multimedia communication and security. He is a member of the ACM. He received the ComManTel 2014, ComComAP 2014, Chinacom 2014, and Qshine 2016 Best Paper Awards. He has served as a co-chair of over 50 international conferences/workshops, and as a technical program committee member of over 150 conferences. He has served on the Editorial Board of up to 14 international journals, including the IEEE Access, the *Telecommunication Systems*, the *International Journal of Ad Hoc and Ubiquitous Computing*, the *Journal of Internet Technology*,and the *KSII Transactions on Internet and Information Systems*. He guest edited a number of special issues in IEEE Journals and Magazines. He has served as a reviewer of over 50 journals.



LINA ZHOU received the B.S. degree from Hohai University, Changzhou, China, in 2015, where she is currently pursuing the M.S. degree with the College of Internet of Things Engineering. Her research interests include localization for wireless sensor networks.



LI LIU received the B.S. degree from Hohai University, Changzhou, China, in 2014, where he is currently pursuing the Ph.D. degree with the College of Internet of Things Engineering. His research interests include coverage and connectivity for wireless sensor networks.