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DV-Hop Localization With Protocol Sequence Based Access

Linqing Gui , Xinyu Huang, Fu Xiao , *Member, IEEE*, Yijin Zhang , *Member, IEEE*, Feng Shu , Jun Wei, and Thierry Val

I. INTRODUCTION

Abstract—Among typical range-free localization schemes for sensor networks, DV-Hop has its distinguishing advantage of the capability to localize unknown nodes, which have less than three or even no neighbor anchors. However, existing DV-Hop based localization methods have not considered the problem of packet collisions, which can frequently happen during the throughout-whole-network broadcast of numerous data packets at the first two steps of DV-Hop. In order to effectively improve the success rate of packet transmission between nodes, this paper proposes a medium access control (MAC) method based on Chinese Remainder Theorem (CRT) protocol sequence for DV-Hop localization. First, a broadcasting strategy is designed for the proposed MAC method. Then, dedicated procedures for both anchor nodes and unknown nodes are presented to implement the designed MAC method in DV-Hop localization. Through simulation and evaluation, the performance of DV-Hop localization with the proposed MAC method is thoroughly investigated. Simulation results show that when the number of protocol sequences is larger than a certain number, the proposed MAC method can provide DV-Hop with better localization accuracy than E-CSMA/CA, while keeping similar localization time.

Index Terms—Localization, range-free, distance vector hop (DV-Hop), protocol sequence.

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INTERNET of things (IOT) has been widely deployed in a variety of critical applications, including event detection, disaster relief, home care, object tracking and environment monitoring [1]. An IOT consists of tiny, inexpensive, and low-powered sensor nodes which can dynamically form a network. The limited transmission power of each sensor node restricts its communication range, thus multi-hop transmission is usually required to gather data from remote sensors [2]. The received data are often fully or partially meaningless if the location from where they have been measured is unknown, making the localization of sensor nodes an essential task in multi-hop networks [3]. Localization is also needed to design new energy-efficient location-based techniques for multi-hop routing, data fusion and automatic calibration in large-scale sensor networks [4].

A variety of node localization schemes have been proposed for IOT. These schemes can be categorized as either range-based or range-free [5]. Range-based schemes first utilize Received Signal Strength Indicator (RSSI) [6], Time of Arrival (TOA) [7], Time Difference of Arrival (TDOA) [8], or Angle of Arrival (AOA) [9] to measure the distance or angle from a target node to each anchor node, and then apply trilateration, triangulation or maximum likelihood to determine the position of the target node [10]. Here anchor nodes are those who are aware of their positions. Range-based schemes are supposed to provide accurate localization results, but they have two major drawbacks. First, the ranging information is easily affected by multipath fading, noise and environment variations. Second, special transceivers are always required to precisely measure TOA or AOA, which consumes more energy and increase the overall cost [11]. In contrast, range-free schemes don't possess aforementioned drawbacks because they utilize connectivity information between nodes, while normally having lower localization accuracy than range-based schemes. Thus range-free schemes are preferable for wireless networks which value the cost more than localization accuracy. The cost-effective advantage of range-free schemes makes them attractive for many IOT applications such as the localization of aged people in a large retirement home or clients in a large shopping mall, where localization accuracy of several meters can be accepted especially considering their privacy. Thus in this paper we focus on range-free localization for low-cost sensor networks.

Many range-free schemes have been proposed these years, for example, Centroid [12], Regulated signature distance (RSD) [13], Concentric Anchor Beacon (CAB) [14], Hitball [15], Multidimensional scaling MAP (MDS-MAP) [16], Distance Vector Hop (DV-Hop) [17] and other DV-Hop based algorithms [11],

[18]–[20]. The former four range-free algorithms have a common feature, i.e., they all require each unknown node should have at least 3 neighbor anchor nodes. However, in this paper, we mainly consider IOT application scenarios with low density anchors distributed sparsely. For example, in a network with total 100 nodes, only 10 are anchors and they are deployed sparsely. Since the ratio of anchors to all nodes is low, many unknown nodes have less than three anchors in their neighborhood, while some unknown nodes even have no neighbor anchors. In this case, the former four localization algorithms cannot work properly because they have restricted requirement on the minimum number of neighbor anchors. Alternatively, flexible and dynamic localization algorithms such as MDS-MAP and DV-Hop are recommended. Since MDS-MAP is known as a centralized algorithm due to its relatively high computation complexity, DV-Hop is preferable for Ad Hoc sensor networks.

The basic principle of original DV-Hop algorithm is that each node first obtains the positions of anchors as well as hop counts to anchors through the flood of information, then each anchor calculates its distance-per-hop and floods this value, finally each unknown node calculates its distance to each anchor and estimates its position. Since the localization accuracy of the original DV-Hop is not satisfying, many algorithms have been proposed to improve the accuracy, for example, Advanced DV-Hop [18], Selective 3-Anchor DV-Hop [19], Reference Anchor Selection-based DV-Hop (RAS DV-Hop) [20] and DV-maxHop [21]. However, these DV-Hop based algorithms have not considered the problem of packet collisions, which can frequently happen during the throughout-network broadcast of position packets and distance-per-hop packets at the first two steps of DV-Hop.

In order to reduce packet collisions during information exchange between nodes, medium access control (MAC) methods are required. There exist some widely-used methods such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and Time Division Multiple Access (TDMA). However, CSMA/CA cannot function well for DV-Hop because it requires the feedback of acknowledgment (ACK) signals to ensure successful receptions. But ACK signals are not necessary for DV-Hop for the following reason. A node normally has no prior knowledge of all neighbor nodes. Then since all the communication in DV-Hop is broadcast, when a node broadcasts a packet, it doesn't know exactly who should receive the packet. Even if the transmitter got some ACK signals from neighbor nodes, it was still not sure whether all neighbors had successfully received the packet. On the other hand, TDMA as a deterministic method can effectively minimize the collisions. However, TDMA has rigid requirements on the system design [22], especially the synchronization, including both frame synchronization and slot synchronization. The rigid synchronization increases overall costs of the network, making most TDMA-based methods [23], [24] not suitable for low-cost and large-scale IOT. Alternatively, in this paper, protocol sequences are recommended, because they have less rigid synchronization requirement than TDMA but provide good and cost-effective performance for DV-Hop.

Protocol sequences are originally proposed to achieve zero-error capacity of a collision channel without feedback [25], [26]. Several types of protocol sequences have been constructed over these years, such as wobbling sequences [27], shift-invariant sequences [28], [29] and Chinese Remainder Theorem (CRT)

sequences [30], [31]. The type of protocol sequences considered in this paper for DV-Hop localization is CRT sequences. Compared to other types of protocol sequences, CRT sequences are able to provide an excellent tradeoff between the worst-case throughput and sequence period [32], [33]. This feature is preferable for DV-Hop localization in which both localization accuracy and delay should meet predefined Quality-of-Service (QoS) requirement.

To the best of our knowledge, this is the first paper discussing protocol sequence based MAC method which can solve the problem about unsuccessful receptions caused by packet collisions in DV-Hop localization. Our proposed method can bring much more successful receptions at the first two steps of DV-Hop, thus effectively improve the localization accuracy. The main contributions of this paper are as follows.

(1) We design a broadcasting strategy for protocol sequence based medium access method. The designed strategy makes protocol sequence applicable to DV-Hop localization. In DV-Hop the nodes not only relay broadcast frames but also have to simultaneously receive frames. Our proposed broadcasting strategy can make the best use of each slot in protocol sequence to fulfill continuous and concurrent transmission/reception at half-duplex nodes. Therefore, based on our designed broadcasting strategy, protocol sequence based MAC method can well fit DV-Hop localization.

(2) We implement the proposed CRT sequence based medium access method at the first two steps of DV-Hop localization. Our proposed method can greatly increase successful receptions during the broadcast in DV-Hop, resulting in higher localization accuracy. Since anchors and unknown nodes follow different procedures in DV-Hop, the implementation of our protocol sequence based MAC method has also been devised separately for anchors and unknown nodes.

(3) We have thoroughly investigated the performance of DV-Hop localization with our proposed CRT sequence based MAC method. Our method is compared to Enhanced-CSMA/CA [11] as well as other protocol sequences such as prime sequences [26]. These methods have been evaluated in terms of localization accuracy and localization time. Simulation results show that with adequate protocol sequences, DV-Hop localization using our method can achieve much better accuracy than other methods, while keeping similar localization time.

The rest of this paper is organized as follows. Section II gives a survey of related works. Section III presents the construction of CRT sequences. Then in Section IV our proposed medium access method for DV-Hop localization is illustrated. Section V introduces simulation scenario and parameters as well as the results and analysis. Conclusions and perspectives are provided in Section VI.

II. RELATED WORK

This section first provides an overview of original DV-Hop localization algorithm as well as some typical DV-Hop based algorithms, for example, Advanced DV-Hop, Selective 3-Anchor DV-Hop, RAS DV-Hop and DV-maxHop. Then, in order to solve the problem of packet collisions in DV-Hop localization, candidate medium access methods are introduced including CSMA/CA, Enhanced-CSMA/CA (E-CSMA/CA), TDMA and protocol sequences.

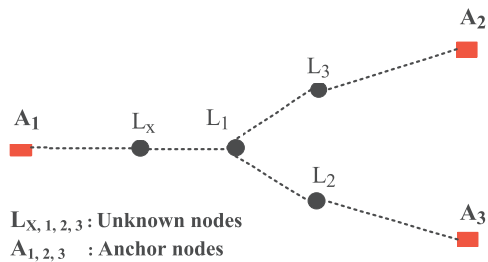


Fig. 1. Example of a small network.

The original DV-Hop algorithm consists of three steps [17]. At the first step, each anchor A_i (shown in Fig. 1) broadcasts a message containing its location and a hop count (0). This hop count will increase during the throughout-network broadcast of the message. The first time receiving the message, every node records A_i 's position, increases the hop count by 1, assigns the increased value to hop_i (its minimum hop count to A_i) and broadcasts the message. The node will maintain hop_i when it receives the message again. Only when the hop count in the message is lower than hop_i , the node updates hop_i and broadcasts the message. Through the first step, every node can obtain its minimum hop counts to all anchors.

At the second step, each anchor calculates and broadcast its average distance-per-hop, which is computed as the sum of distances to other anchors divided by the sum of smallest hop counts to other anchors [17]. The first time receiving an anchor's distance-per-hop, every node will record it and help to broadcast it. Through the second step, every unknown node can obtain average distance-per-hop of all anchors.

At the third step, using the hop counts and distance-per-hop values received at previous two steps, each unknown node L_x can estimate its distances to all anchors. Then with the positions of all anchors, L_x can finally calculate its geometrical position through trilateration or multi-lateration.

Although the original DV-Hop algorithm can localize those unknown nodes with less than 3 neighbor anchors, its accuracy is quite low. Many DV-Hop based algorithms [18]–[21] have been proposed over these years to improve localization accuracy. However, these algorithms neglected the problems at MAC layer, e.g., packet collisions during the throughout-network broadcast of position/distance-per-hop packets at the first two steps of DV-Hop. In order to reduce packet collisions and improve transmission success rate in DV-Hop localization, medium access methods are required.

CSMA/CA and TDMA are two widely-used methods for accessing the medium. As a random method, although CSMA/CA has been adopted by WiFi and ZigBee, it cannot effectively reduce packet collisions for DV-Hop localization because of two reasons. First, the traffic by throughout-network broadcast in DV-Hop is too heavy. Second, ACK signals are not available. Thus the traditional CSMA/CA is unable to ensure successful data reception in DV-Hop. Then Enhanced-CSMA/CA (E-CSMA/CA) was proposed in [11] to reduce collisions by lowering the chance of simultaneous transmissions, but at the cost of additional transmission delay. However, there still exist many collisions especially in large-scale networks. On the other hand, aiming to provide collision-free transmission, TDMA is a well-known schedule-based MAC technique [22]. Although TDMA saves energy loss by avoiding collision, it still has

several issues such as rigid requirement on time synchronization, slot wastage in sparse networks [22] and poor flexibility to handle adaptive data traffic (especially for static TDMA methods).

In ad-hoc sensor networks, well-coordinated transmission and time synchronization may be difficult to achieve because of energy constraints, time-varying channel conditions and user mobility. Thus a simple medium access method is desirable, which requires neither rigid time synchronization nor frequent channel sensing. Protocol sequences, as deterministic coding sequences for accessing a collision channel without feedback, can be a good choice [25]. Using protocol sequence based medium access method, it is not necessary for the transmitters to synchronize with each other. Thus unlike TDMA, rigid time synchronization is not required. Whereas compared with CSMA/CA, protocol sequences don't require channel monitoring, back off algorithm or packet retransmission.

In order to obtain a good trade-off between the worst-case throughput and sequence period, Chinese Remainder Theorem (CRT) protocol sequences were proposed in [30]. Recent applications of CRT sequences can be found in [31]–[33]. CRT sequences are binary sequences whose pairwise Hamming cross-correlation is highly concentrated around the mean. With the special Hamming cross-correlation property, CRT sequences can provide a hard guarantee on the worst-case system throughput, which is lower bounded by a positive constant no matter what the delay offsets are [30]. CRT sequences have several remarkable advantages. First, CRT sequences possess shorter period than existing protocol sequences with the same throughput performance [34]. Second, the generation of CRT sequences involves only simple modular arithmetic, thus a low-complexity solution can be provided for medium access control in IOT [30]. Third, CRT sequences have two capabilities, i.e., user identification and frame-synchronization capability. Due to the aforementioned advantages, CRT sequence-based MAC method can be a good choice for DV-Hop localization.

III. CONSTRUCTION OF CRT PROTOCOL SEQUENCES

As for binary sequences, the characteristic set is defined as the set of locations of the ones in a period of a sequence. So a sequence can be represented in a compact way by specifying the characteristic set of the sequence. Given a sequence $a(k)$ of length L , let I_a be the characteristic set of $a(k)$. Then the number $k \in I_a$ if and only if $a(k) = 1$. Let \mathbb{Z}_n be the ring of residues mod n for a positive integer n . If the length of a sequence is L , \mathbb{Z}_L represents the time indices $0, 1, 2, \dots, L-1$. Then I_a , the characteristic set of $a(k)$, is the subset of \mathbb{Z}_L .

We construct sequences with length $L = pq$, where p and q are relatively prime integers. In the following discussions, p is a prime number and q is an integer not divisible by p . Based on Chinese remainder theorem [34], the mapping $f : \mathbb{Z}_{pq} \rightarrow \mathbb{Z}_p \oplus \mathbb{Z}_q$ defined by $f(x) := (x \bmod p, x \bmod q)$ is a bijection from \mathbb{Z}_{pq} to $\mathbb{Z}_p \oplus \mathbb{Z}_q$. Since I_a is the subset of \mathbb{Z}_{pq} , the characteristic set can be mapped to a subset of $\mathbb{Z}_p \oplus \mathbb{Z}_q$, which consists of ordered pairs in the form (w, v) with $0 \leq w < p$ and $0 \leq v < q$. We will construct sequences by specifying characteristic sets in $\mathbb{Z}_p \oplus \mathbb{Z}_q$.

CRT construction [30]: Given the number of sensor nodes K , we set p to be the smallest prime equal to or larger than K and

q to be $kp - 1$ ($k \geq 2$). For $g = 0, 1, p - 1$, we let

$$I'_{g,p,q} = \{(gt \bmod p, t) \in \mathbb{Z}_p \oplus \mathbb{Z}_q : t = 0, 1, \dots, q - 1\} \quad (1)$$

Then we obtain the characteristic set I_g in \mathbb{Z}_{pq} by taking the inverse image $f^{-1}(I'_{g,p,q})$. The CRT construction produces p sequences of sequence period pq and Hamming weight q . Here, the Hamming weight of a sequence is the number of ones in a sequence period.

Definition 1: (CRT sequences) For $g = 0, 1, \dots, p - 1$, define the CRT sequence generated by I_g , denoted by $s_g(t)$, be the binary sequence of length L obtained by setting

$$s_g(t) = \begin{cases} 1, & \text{if } t \in I_g, \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

We will write $s_g(t)$ if the values of p and q are understood.

Example 1: $p=3$ and $q=5$. The three characteristic sets are

$$\begin{aligned} I'_{0,3,5} &= \{(0,0), (0,1), (0,2), (0,3), (0,4)\} \\ I'_{1,3,5} &= \{(0,0), (1,1), (2,2), (0,3), (1,4)\} \\ I'_{2,3,5} &= \{(0,0), (2,1), (1,2), (0,3), (2,4)\} \end{aligned} \quad (3)$$

By taking the inverse image of $I'_{g,p,q}$, we obtain I_g as

$$\begin{aligned} I_0 &= \{0, 3, 6, 9, 12\} \\ I_1 &= \{0, 1, 2, 3, 4\} \\ I_2 &= \{0, 3, 7, 11, 14\} \end{aligned} \quad (4)$$

The generated CRT sequences are listed as follows:

$$\begin{aligned} s_0 &= [100100100100100] \\ s_1 &= [111110000000000] \\ s_2 &= [100100010001001] \end{aligned} \quad (5)$$

IV. PROTOCOL SEQUENCE-BASED MAC METHOD FOR DV-HOP LOCALIZATION

This section presents a CRT protocol sequence-based medium access method for DV-Hop localization. The proposed method pre-allocates a CRT sequence for each sensor node and uses this sequence to control packet broadcasting. In this paper, it is assumed that the network is beacon enabled and slots are synchronized.

A. Allocation of CRT Sequences

It is supposed that in a network there are K sensor nodes and the number of CRT sequences is p . These p sequences are allocated by network administrator to the K sensor nodes for data transmission. The period of each sequence is denoted as L which can be calculated as $L = pq$. Here, p and q are relatively prime numbers and q equals to $kp - 1$.

Conventionally, p can be the smallest prime number greater or equal to the number of sensor nodes K . This can assure that every sensor node has one unique protocol sequence for data transmission. However, in practice the network can have a large number of sensor nodes. If p is still greater or equal than K then the period of CRT sequence will become very long and one successful transmission will take much time which will increase the system delay. Therefore, for a network with a large number

of sensor nodes, it is recommended that the number of CRT sequences p is smaller than K .

The allocation of protocol sequences is presented as follows. If $S = \{S(j), j = 1, 2, \dots, p\}$ denote the protocol sequences before allocation, then the protocol sequence allocated to the i^{th} sensor node, denoted as PS_i , can be expressed as

$$PS_i = S(\text{mod}(i, p) + 1) \quad (6)$$

Here, $\text{mod}(i, p)$ is used because the number of sensor nodes K can be bigger than the number of CRT sequences p .

If p is larger than K , every sensor node can surely have one protocol sequence. In this case the data of each sensor node can be transmitted successfully at least once, i.e., unknown node can successfully receive the data from each sensor node. However when p is smaller than K , there should exist several sensor nodes sharing the same protocol sequence. In this case the data from those sensor nodes may collide with each other if those nodes begin their sequences simultaneously. But the probability of collisions can be reduced if each sensor node randomly cyclic-shifts the allocated protocol sequence before transmission. This can be illustrated by the following example.

As an example, p is set to 3, K is 5 and q is 5. Then L becomes 15. At the first step of sequence allocation, CRT sequences are obtained by the construction as Eq. (5).

At the second step, according to Eq. (6) the protocol sequences are allocated to the five nodes as

$$\begin{aligned} PS_1 &= [111110000000000] \\ PS_2 &= [100100010001001] \\ PS_3 &= [100100100100100] \\ PS_4 &= [111110000000000] \\ PS_5 &= [100100010001001] \end{aligned} \quad (7)$$

At the third step, the sensor nodes will randomly cyclic-shift the allocated protocol sequences. Here, we give two random examples. The first example is that the numbers of slots to be shifted in the protocol sequences of the five sensor nodes are assumed to be 1, 2, 3, 4 and 5 respectively. Then the final protocol sequences for actual transmission are

$$\begin{aligned} PS_1 &= [011111000000000] \\ PS_2 &= [011001000100010] \\ PS_3 &= [100100100100100] \\ PS_4 &= [000011111000000] \\ PS_5 &= [010011001000100] \end{aligned} \quad (8)$$

In this example, the data of the first node will not be successfully received because it transmits at the 2^{nd} , 3^{rd} , 4^{th} , 5^{th} and 6^{th} slot and collisions happen at all these slots. (It is assumed that the maximum length of data packets cannot exceed one slot duration.) As for the fifth node, the node has not successfully transmitted data packet on the 2^{nd} , 5^{th} , 6^{th} , 9^{th} and 13^{th} slots because of collisions. On the other side, the other three nodes can successfully transmit their data, i.e., the second, third and fourth nodes can successfully transmit the data at the 14^{th} , 1^{st} and 8^{th} slots, respectively.

As for the other example, the numbers of slots to be shifted in the protocol sequences of the five nodes are assumed to be 7,

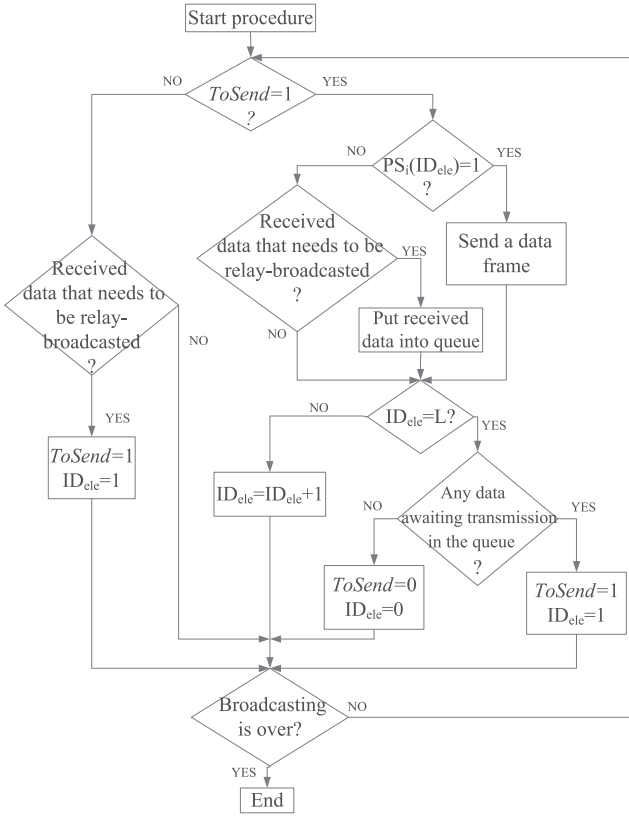


Fig. 2. Procedure of protocol sequence based broadcasting.

2, 3, 4 and 7 respectively. Then the final protocol sequences for actual transmission are

$$\begin{aligned}
 PS_1 &= [000000011111000] \\
 PS_2 &= [011001000100010] \\
 PS_3 &= [100100100100100] \\
 PS_4 &= [000011111000000] \\
 PS_5 &= [000100110010001]
 \end{aligned} \tag{9}$$

In this case all the five nodes can successfully transmit their data at least once. From these two examples, we can see that when the number of protocol sequences p is smaller than the number of sensor nodes K , data from some nodes may not be successfully received. But if each node randomly cyclic-shifts the allocated protocol sequence, there is a chance for all sensor nodes to transmit the data successfully at least once.

B. Broadcasting Strategy of Protocol Sequence Based MAC Method

Due to multiple transmissions of the same data frame, our proposed MAC method is supposed to effectively increase successful receptions at the first two steps of DV-Hop, thus improve localization accuracy. Then our designed broadcasting strategy can make the proposed MAC method well applicable to DV-Hop localization. The procedure of protocol sequence based broadcasting strategy is shown in Fig. 2. All transmissions are assumed to be half-duplex.

Protocol sequences are used by the nodes for data transmission. Therefore, when a node has a data frame to send, it can

start one period of protocol sequence. When a node has no data frame to send, although not yet start a protocol sequence, it can receive data frames from other nodes. So, we divide the procedure into two cases: a node has a data frame to send or has no data frame. The detail procedure corresponding to the two cases are described in the following.

1) A node has a data frame to send

In this case, a node has a data frame to send, but whether it can broadcast a data frame at the current slot depends on the value of the current element of the protocol sequence. It should be noted that the duration of each element of the protocol sequence is equivalent to the duration of one time slot. The broadcasting procedure in this case consists of the following two steps.

At the first step, a node checks the value of the current element of the allocated protocol sequence. If this value (denoted as $PS_i(ID_{ele})$) equals to 1, the node can broadcast the data frame. If the value is 0, the node cannot broadcast the data frame at the current slot, but it can receive a data frame from neighbor nodes. At this time, if the node really receives some data frame from neighbor nodes, then the node puts the received data frame into its queue. The received data will be broadcasted in the next period of the protocol sequence.

At the second step, the node checks whether it reaches the end of the current period of protocol sequence. If the ID of the current element of the sequence (denoted as ID_{ele}) is less than the length of the sequence, indicating the current period of the protocol sequence has not yet finished, then the node will go into the next slot to continue the current period and run the first step again.

On the other hand, if ID_{ele} equals to the length of the sequence, indicating the end of the current period, then the node will check whether it has any data frame in its queue. If the node has some data frame in the queue, then the node will start a new period of the sequence in the next slot to broadcast this data frame. If there is no data frame in the queue, then the node cannot start a new period of the sequence, thus the procedure goes to the other case which will be introduced next.

2) A node has no data frame to send

In this case, a node has no data to broadcast at the current time slot, but it can receive data frames from neighbor nodes. At this time, if the node really receives a data frame, then the node will start a new period of the protocol sequence in the next slot to broadcast the received frame. On the other hand, if the node does not receive any data frame from neighbor nodes at the current slot, the node will continue in the next slot to check whether it can receive some data frame.

The above two-case procedure has illustrated the broadcasting strategy for protocol sequence-based MAC method. The proposed strategy can make the best use of each slot in protocol sequence to fulfill continuous and concurrent transmission/reception at half-duplex nodes. Thus the proposed broadcasting strategy makes protocol sequence based MAC method well applicable to DV-Hop localization.

C. Implementation of Protocol Sequence Based MAC Method in DV-Hop Localization

In DV-Hop localization, anchor nodes follow a different procedure than unknown nodes. During one localization period, each anchor node operates two steps, while each unknown node

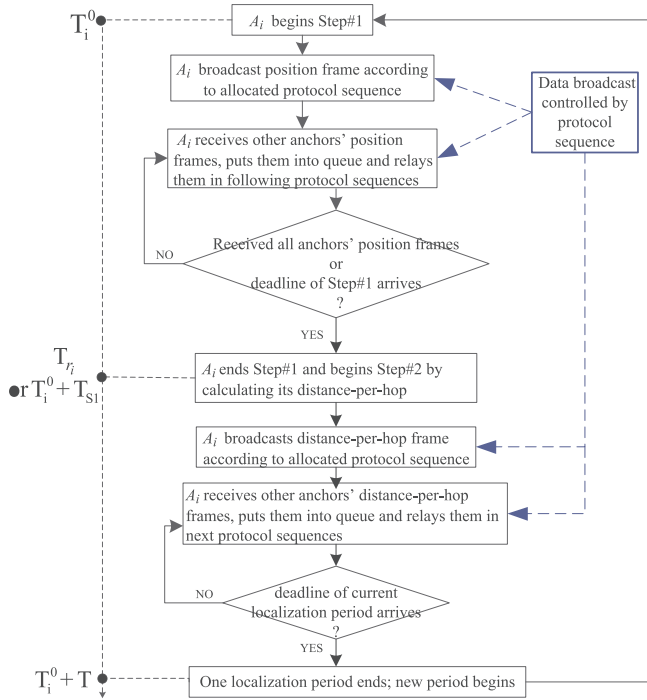


Fig. 3. Procedure for each anchor node A_i .

has an additional calculation step (the third step). At the first step, each anchor node broadcasts throughout the network its position frame which composes of its ID, its position and a hop count value initialized as 0. Meanwhile, at this step every node can receive position frames originated from anchor nodes and help to relay broadcasting these frames. In order to avoid endless relay, the relay broadcasting should obey the update mechanism designed in the original DV-Hop algorithm. Through this whole-network broadcast, if there are no collisions, all nodes are able to acquire the position of each anchor as well as their minimum hop counts to each anchor. At the second step, each anchor node broadcasts its distance-per-hop frame which contains the ID of the anchor as well as its distance per hop. Meanwhile, each unknown node can also receive the distance-per-hop frames and help to relay them.

Since anchor nodes and unknown nodes follow aforementioned different procedures, the implementation of protocol sequence based MAC method will be presented for anchor nodes and unknown nodes separately. Figure 3 shows the procedure followed by each anchor node A_i . A_i begins its localization period at the time T_i^0 . Then, according to our protocol sequence based medium access method, if the value of current element of the allocated protocol sequence is 1, A_i is allowed to broadcast its position frame to its neighbors. If the value is 0, A_i cannot broadcast the position frame to its neighbors at the current slot, but it can receive position frames from neighbor nodes. When A_i really receives some position frame from neighbor nodes, the received position frame will be put into the queue. This received position frame will be broadcasted in the next period of protocol sequence.

When A_i has received all anchors' position frames, it will immediately end the first step and enters the second step. This time instant is denoted as T_{r_i} in Fig. 3. Otherwise, if A_i could not

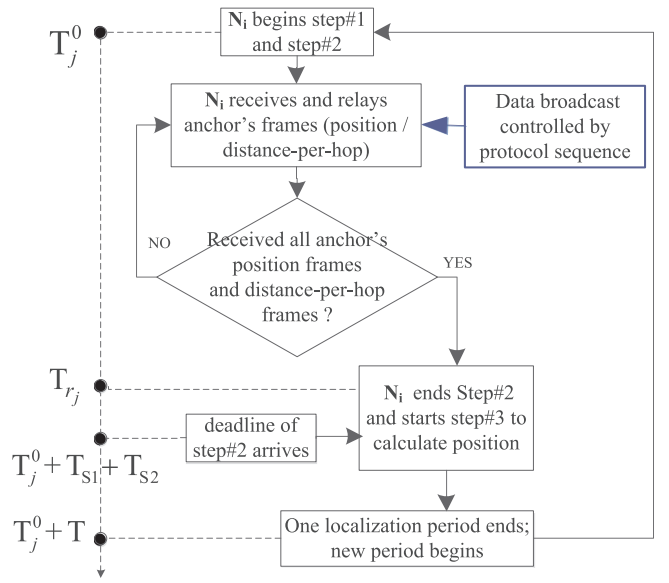


Fig. 4. Procedure for each unknown node N_i .

receive all anchors' position frames until the deadline $T_i^0 + T_{s1}$, A_i will nevertheless end the first step. With these two cases taken into consideration, A_i ends the first step at the time T_{r_i} or $T_i^0 + T_{s1}$.

A_i begins the second step by calculating its distance-per-hop. Then according to the broadcasting strategy of protocol sequence based medium access, A_i broadcasts its distance-per-hop frame to its neighbors if the current element of the sequence is 1. If the value is 0, A_i is not allowed to broadcast its distance-per-hop frame, but A_i can receive other anchors' distance-per-hop frames from neighbor nodes. The received distance-per-hop frame will be put into its queue and will be broadcasted in the next period of protocol sequence. When A_i ends the second step, it also ends one localization period, because only unknown nodes participate in the third step. Then A_i will start a new localization period and repeat the aforementioned steps. Here the maximum duration of one localization period is denoted as T .

Fig. 4 shows the procedure for each unknown node N_i . N_i begins its localization period at the time T_j^0 . During the first two steps, N_i receives and relays anchors' data frames including anchors' position frames and distance-per-hop frames. If N_i really receives a data frame from its neighbors, it will record the information in the frame and check whether it should relay broadcasting the frame according to the update mechanism designed in the original DV-Hop algorithm. If it needs to relay the frame, it will start a new period of its allocated protocol sequence and transmit the data frame according to the protocol sequence. When N_i has received all anchors' position frames and distance-per-hop frames at least once, it will immediately end the first two steps. However, if N_i could not receive all anchors' position frames and distance-per-hop frames at least once until the time $T_j^0 + T_{s1} + T_{s2}$, N_i will nevertheless end the first two steps. Then, N_i enters the third step to calculate its position based on the information received at the first two steps. Finally, N_i ends one localization period at the time $T_j^0 + T$ and restarts a new period.

TABLE I
SIMULATION PARAMETERS AND THEIR VALUES

Parameter	Value
Number of nodes: K	100
Communication range of each node	25 m
Ratio of anchor nodes	5% to 40%
Transmission data rate of each node	250 kbps
Duration of each slot	0.576 ms
Maximum duration of one localization period T	5.76 s
Maximum duration of the first step T_{s1}	2.88 s
Maximum duration of the second step T_{s2}	2.16 s
Maximum duration of the third step	0.72 s
Number of protocol sequences p	5, 7 and 11
Maximum waiting time of each anchor node t_{wa}	0.576 s
Maximum waiting time of each relay node t_r	5.76 ms

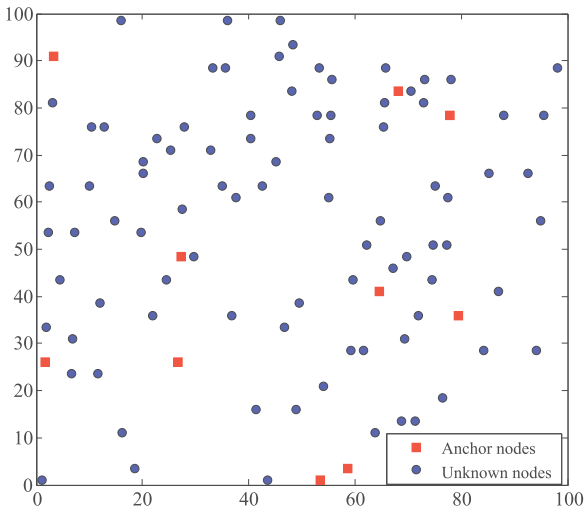


Fig. 5. Example of a network with 10 anchor nodes.

V. SIMULATION AND ANALYSIS

Using MATLAB, we simulate the DV-Hop localization protocol with three candidate medium access methods. The three methods are CRT sequence based medium access method, prime sequence based medium access method [26] and the slotted version of E-CSMA/CA [11]. In the following, we first introduce the simulation scenario and parameters, then present the simulation results and give the analysis.

A. Simulation Scenario

As listed in Table I, our simulation scenario takes place within a $100 \times 100m^2$ area. Inside this area, 100 nodes including anchors and unknown nodes are randomly placed with the communication range of 25 m. The ratio of anchor nodes can range from 5% to 40%. An example of the network is given in Fig. 5 where the number of anchor nodes is 10.

As for the synchronization, all the sensor nodes are slot synchronized but not frame synchronized because all nodes may

start their protocol sequence at different time. Thus we consider slot synchronous model in which the slot boundaries of nodes are aligned. Two data frames from two different nodes will either overlap completely or not overlap at all. Since the protocol sequences need not to start at the same time, the relative delay offsets between two nodes are integral multiple of the duration of one time slot.

The duration of slot is calculated as follows. Since one slot can transmit not only position frame but also distance-per-hop frame, the length of the longer frame between these two frames will be assigned to the duration of one slot. First, the lengths of both frames are calculated. Conforming to data frame formats in IEEE standard 802.15.4 [35], the position frame have three parts including frame header (7 bytes), data payload (9 bytes) and check sequence (2 bytes). Here, the data payload has 9 bytes because it contain an 8-byte position of the corresponding anchor node and 1-byte hop count to the anchor. So the length of a position frame is 18 bytes, equivalent to 144 bits if one byte equals 8 bits. The difference between distance-per-hop frame and position frame is the content of data payload. Only containing 4-byte distance-per-hop in data payload, each distance-per-hop frame has 13 bytes, equivalent to 104 bits. Since the position frame is longer, the duration of one slot is set to that of a position frame, i.e., 144 bits. If data rate is 250 kbps, then the duration of each slot is 0.576 ms.

The maximum duration of the first step is denoted as T_{s1} , whereas T_{s2} is used to represent the maximum duration of the second step. In DV-Hop algorithm, all data broadcast is included at the first two steps, while the third step is dedicated for position calculation. Since the broadcast normally takes much more time than the calculation, the maximum duration of the first two steps is very close to the entire period of localization (denoted as T). Besides, since the first step and the second step both broadcast data frames, their duration should be similar. As an example, we can set T_{s1} to be $T/2$ and T_{s2} to be $3T/8$. Then, the maximum duration of the third step is $T - T_{s1} - T_{s2} = T/8$. We assume T to be 5.76 s, obtained by multiplying the duration of each slot (0.576 ms) by the number of slots assumed as 10000, which should be sufficient to cover the most distant end-to-end transmission in the network at the first two steps of DV-Hop. Then, the maximum durations of the three steps of DV-Hop are calculated to be 2.88 s, 2.16 s and 0.72 s respectively.

As discussed previously, the number of protocol sequences (denoted as p) is supposed to be smaller than the number of sensor nodes K , because a large p would increase the period of protocol sequences and then the transmission over one sequence would take much more time which increases the system delay. Therefore, we set p to 5, 7, and 11.

Dedicated for the slotted version of E-CSMA/CA, the maximum random waiting time of each anchor node before performing CSMA/CA, denoted as t_{wa} , is set to 0.576 s. Here t_{wa} cannot be too small; otherwise, different anchors probably send their position/distance-per-hop frames at similar time, causing more collisions. In addition, the maximum random waiting time of each relay node (either anchor or unknown node) in E-CSMA/CA, denoted as t_r , is set to 5.76 ms.

B. Simulation Results and Analysis

In this section, we simulate and compare four DV-Hop localization protocols, i.e., DV-Hop-ideal, DV-Hop-E-CSMA/CA,

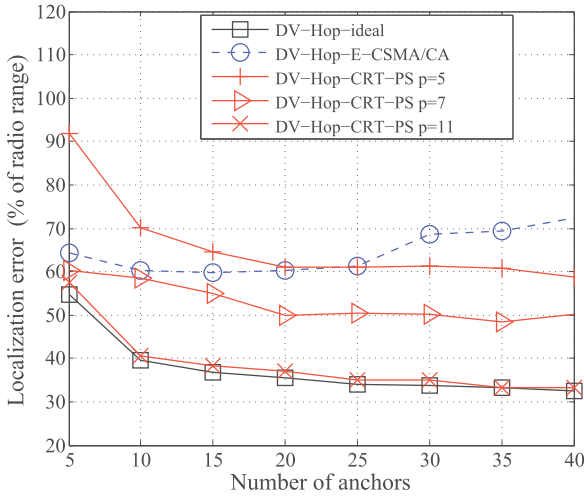


Fig. 6. Average localization errors of 3 different DV-Hop localization protocols.

DV-Hop-CRT-PS and DV-Hop-Prime-PS. Here, DV-Hop-ideal is the ideal DV-Hop localization without collisions and DV-Hop-E-CSMA/CA represents DV-Hop localization protocol with the slotted version of E-CSMA/CA. Both DV-Hop-CRT-PS and DV-Hop-Prime-PS are DV-Hop localization protocols with protocol sequence based medium access method, but they use different protocol sequences (CRT sequences and prime sequences respectively). The aforementioned DV-Hop localization protocols are compared in terms of average localization error and average localization time. Localization error is normally defined as the Euclidean distance between an unknown node's estimated position and its real position. Here the average localization error (in percentage of communication range) is the mean of all unknown nodes' localization errors divided by the communication range. The average localization error is used to measure the accuracy, while the average localization time is for measuring the average of all localization delays regarding to all unknown nodes. Here, localization delay of an unknown node is represented by the time required to completing its three steps of DV-Hop localization. The localization delay of an unknown node may be smaller than one localization period, because the period equals the maximum duration of the total three steps, while the node may end the first two steps in advance.

Fig. 6 shows how localization errors of different DV-Hop localization protocols change with the number of anchors. As for DV-Hop-CRT-PS, it is observed that the accuracy becomes better when the number of anchors increases. Two reasons are given as follows. First, when more anchors join the network, each unknown node can get more useful information including the positions of the new anchors and the hop counts to them. The second reason is that with more anchors in the same area, an unknown node could be closer to some anchors, then the distance estimation between each anchor and the unknown node should be less erroneous.

As for DV-Hop-ECSMA/CA, when the number of anchors increases (at most 20), the accuracy also improves. But the accuracy becomes worse when the number of anchors increases from 20. The reason is that with so many anchors, the network traffic becomes heavy, causing considerable collisions. These

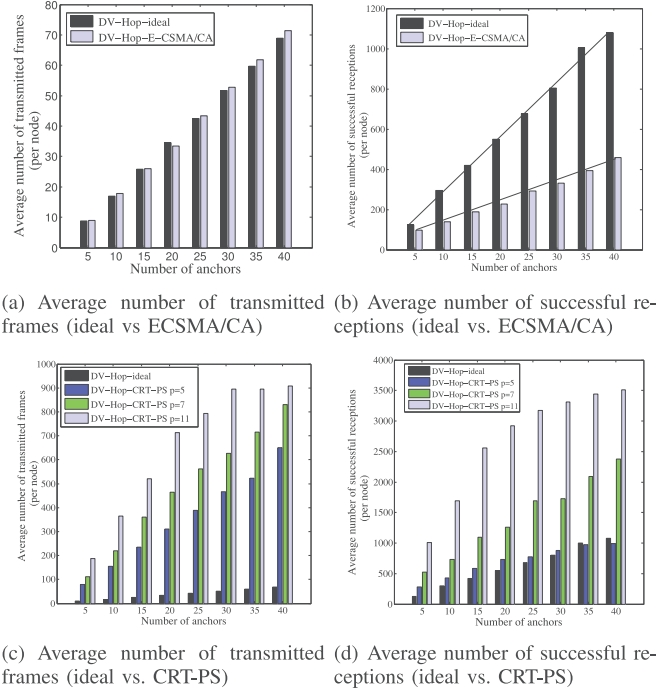


Fig. 7. Average number of transmitted frames and the average number of successful receptions.

collisions will prevent unknown nodes from receiving the right position frame that has the smallest hop count. The increased collisions can also be deduced from Fig. 7 (a) and (b) on the number of transmitted frames and the number of successful receptions. Both quantities are counted for all nodes during one localization period and then averaged per node. Observed from subfigure (a) and (b), though DV-Hop-E-CSMA/CA has similar number of transmitted frames to DV-Hop-ideal, its successful receptions are much fewer, indicating that many frames have been destroyed by collisions.

In Fig. 6 we notice that DV-Hop-CRT-PS (with p greater than 5) has better accuracy than DV-Hop-E-CSMA/CA. The reason is explained as follows. In DV-Hop-CRT-PS each anchor broadcasts its position frame multiple times during one protocol sequence. Although more collisions may occur, unknown nodes have much more chance to receive the right position frames. This can also be supported by the results shown in Fig. 7(d) where DV-Hop-CRT-PS (with p greater than 5) has much more successful receptions than DV-Hop-ideal. The good performance of DV-Hop-CRT-PS is achieved at the cost of additional transmissions as shown in Fig. 7(c).

From Fig. 6, it is also observed that the localization accuracy of DV-Hop-CRT-PS gets better when p increases. Two reasons can be given. The first reason is that as p increases, with more protocol sequences the possibility of several nodes sharing the same protocol sequence becomes smaller, resulting greater probability to successfully receive data frames. As the second reason, when p increases, the anchors will broadcast more replicas of position frames or distance-per-hop frames during one protocol sequence. Due to these two reasons, unknown nodes can receive more right position frames from anchors, so that they can obtain less erroneous estimated distance. Thus a larger p can bring better accuracy to DV-Hop-CRT-PS. Although not good

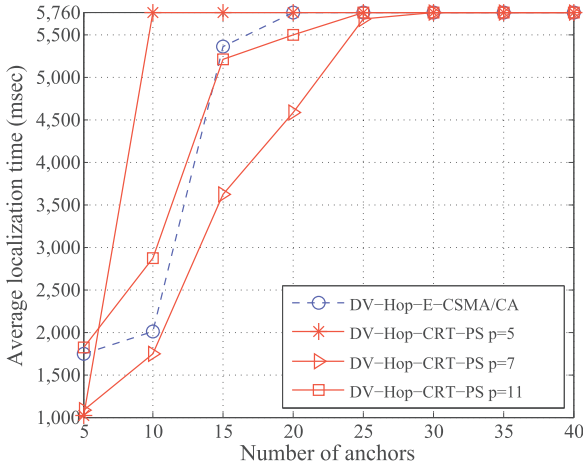


Fig. 8. Average localization time of 3 different DV-Hop localization protocols.

as DV-Hop-E-CSMA/CA when p is 5, the performance of DV-Hop-CRT-PS becomes better than DV-Hop-E-CSMA/CA when p goes beyond 5. It can also be observed from Fig. 6 that when p equals to 11, the localization accuracy of DV-Hop-CRT-PS is close to DV-Hop-ideal.

Fig. 8 shows that the average localization time of different DV-Hop localization protocols increases with the number of anchor nodes. Two reasons can be given to explain this. As the first reason, since each anchor needs to broadcast its position frame and distance-per-hop frame throughout the network, if there are more anchors, each unknown node will take more time to receive all anchors' frames. The second reason is that when there are more anchors, the traffic in the network increases (as shown in Fig. 7(a) and 7(c)), which leads to more collisions. Due to the increased collisions, unknown nodes lose more data frames from some anchors, then they have to wait for additional time to try retrieving the frames from those anchors. Due to these two reasons, when there are more anchors, the localization time of DV-Hop localization protocols increases.

Shown in Fig. 8, from the curve corresponding to p being 5, it can be observed that when the number of anchors is 5, the average localization time of DV-Hop-CRT-PS is short. But when the number of anchors is no less than 10, the average localization time becomes so long that it reaches the maximum duration of the localization protocol, i.e., 5.76 s. The relatively short localization time in the case of 5 anchors can be explained by two reasons. First, with only 5 anchors, although there exist collisions, each unknown node can still receive at least one position frame and one distance-per-hop frame from every anchor node (but the hop count value inside the received position frame may not be the smallest hop count). Thus each unknown node can still end the first and second steps before the deadline of each step. So the real duration of step 1 (also step 2) doesn't exceed the maximum duration of that step. Therefore the localization time of each unknown node is less than 5.76 s. As the second reason, when p is 5, the length of each protocol sequence is short, thus it will take short time to complete the transmission of all replicas of data frames in each protocol sequence. Due to these two reasons, the average localization time is short when there are only 5 anchors. However, when the number of

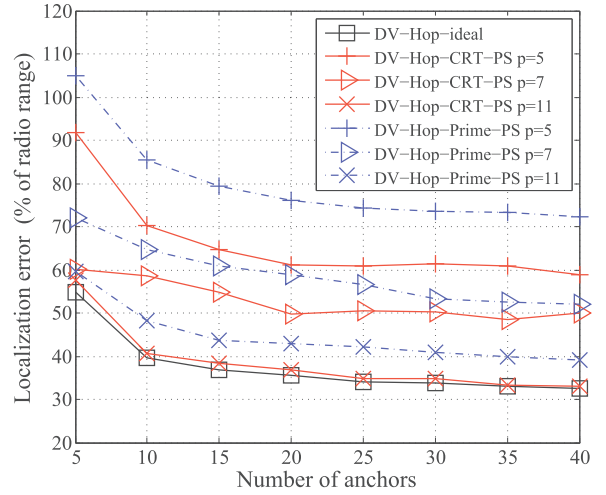


Fig. 9. Average localization errors of protocol sequence based DV-Hop localization protocol.

anchors exceeds 10, the average localization time becomes as long as the maximum duration of one localization period. The reason is that with more anchors, the network traffic increases, resulting in more collisions. Increased collisions will prevent unknown nodes to receive data frames from one or more anchors, so unknown nodes will wait until the deadline of each step of DV-Hop.

As depicted in Fig. 8, when p increases from 7 to 11, the average localization time also increases. The reason is that as p increases, the length of each protocol sequence becomes longer, so it will take more time to transmit all replicas of data frames in each protocol sequence.

From Fig. 9 it can be observed that for the same p , the localization accuracy of DV-hop-CRT-PS is better than DV-hop-Prime-PS. The reason is given as follows. The Hamming weight of DV-hop-CRT-PS denoted as q equals to $2p - 1$, greater than the Hamming weight of DV-hop-Prime-PS. Since Hamming weight is the number of ones in each sequence, increased number of ones will bring more chance to unknown nodes for receiving the right data frames from anchors.

Fig. 10 shows that for the same p , the average localization time of DV-Hop-Prime-PS is shorter than DV-Hop-CRT-PS. As the reason, the length of each prime sequence is p^2 , shorter than the length of each CRT sequence which is $pq = p(kp - 1)$. Thus DV-Hop-Prime-PS will take shorter time to transmit all replicas of data frames in each protocol sequence and the average localization time of DV-Hop-Prime-PS will become shorter. It can also be observed that in the case of p being 5, when the number of anchors is no less than 10, the average localization time of DV-Hop-Prime-PS as well as that of DV-Hop-CRT-PS reaches the maximum duration. The reason is explained as follows. With more anchors, the traffic in the network increases, resulting in more collisions. Increased collisions will prevent unknown nodes to receive data frames from some anchors, so unknown nodes will have to wait and to try retrieving frames from those anchors until the deadline of each step of DV-Hop. Therefore, the average localization time reaches the maximum duration of one localization period.

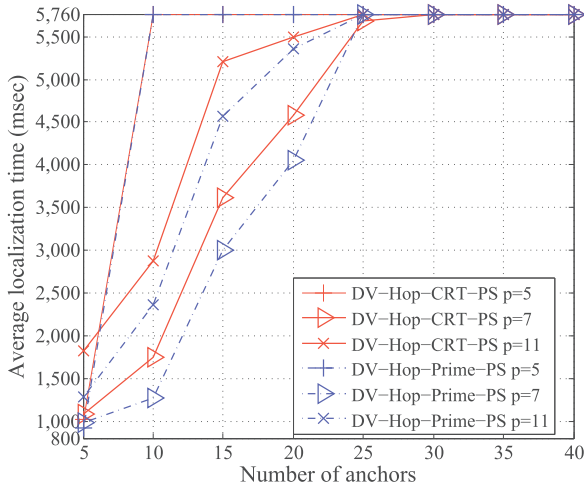


Fig. 10. Average localization time of protocol sequence based DV-Hop localization protocol.

VI. CONCLUSION

In this paper, we propose a CRT protocol sequence-based MAC method for DV-Hop localization. First, we design a broadcasting strategy for protocol sequence based MAC method. This method pre-allocates CRT sequences to all sensor nodes, thus each node can use the allocated sequence to control packet broadcasting at the first two steps of DV-Hop. According to whether a sensor node has a data frame to send or not, two different cases are considered in the broadcasting strategy. For each case, we provide a corresponding procedure. Then we implement the designed protocol sequence medium access method in DV-Hop localization. Through simulation and evaluation, we investigate the performance of DV-Hop localization with our proposed MAC method. Our proposed method is compared with ECSMA/CA and other protocol sequences such as prime sequences, in terms of average localization accuracy and average localization time. Simulation results show that when the number of protocol sequences is larger than a certain number, DV-Hop localization protocol with our proposed CRT protocol sequence based MAC method can achieve better accuracy than that using E-CSMA/CA, while keeping similar localization time.

REFERENCES

- [1] H. Zhu, F. Xiao, L. Sun, R. Wang, and P. Yang, "R-TTWD: Robust device-free through-the-wall detection of moving human with wifi," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 5, pp. 1090–1103, May 2017.
- [2] S. Zaidi, A. E. Assaf, S. Affes, and N. Kandil, "Accurate range-free localization in multi-hop wireless sensor networks," *IEEE Trans. Commun.*, vol. 64, no. 9, pp. 3886–3900, Sep. 2016.
- [3] F. Xiao *et al.*, "Noise tolerant localization for sensor networks," *IEEE/ACM Trans. Netw.*, vol. 26, no. 4, pp. 1–14, Jul. 2018, doi: 10.1109/TNET.2018.2852754.
- [4] F. Xiao, Z. Wang, N. Ye, R. Wang, and X. Y. Li, "One more tag enables fine-grained RFID localization and tracking," *IEEE/ACM Trans. Netw.*, vol. 26, no. 1, pp. 161–174, Feb. 2018.
- [5] C. H. Ou and W. L. He, "Path planning algorithm for mobile anchor-based localization in wireless sensor networks," *IEEE Sensors J.*, vol. 13, no. 2, pp. 466–475, Feb. 2013.
- [6] F. Xiao, W. Liu, Z. Li, L. Chen, and R. Wang, "Noise-tolerant wireless sensor networks localization via multinorms regularized matrix completion," *IEEE Trans. Veh. Technol.*, vol. 67, no. 3, pp. 2409–2419, Mar. 2018.

- [7] F. Despoux, K. Jaffres-Runser, A. van den Bossche, and T. Val, "Accurate and platform-agnostic time-of-flight estimation in ultra-wide band," in *Proc. IEEE 27th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun.*, Sep. 2016, pp. 1–7.
- [8] J. Tiemann and C. Wietfeld, "Scalable and precise multi-UAV indoor navigation using TDOA-based UWB localization," in *Proc. Int. Conf. Indoor Positioning Indoor Navigat.*, Sep. 2017, pp. 1–7.
- [9] F. Shu *et al.*, "Low-complexity and high-resolution DOA estimation for hybrid analog and digital massive mimo receive array," *IEEE Trans. Commun.*, vol. 66, no. 6, pp. 2487–2501, Jun. 2018.
- [10] L. Gui, M. Yang, H. Yu, J. Li, F. Shu, and F. Xiao, "A cramer-rao lower bound of CSI-based indoor localization," *IEEE Trans. Veh. Technol.*, vol. 67, no. 3, pp. 2814–2818, Mar. 2018.
- [11] L. Gui, T. Val, A. Wei, and R. Dalce, "Improvement of range-free localization technology by a novel DV-hop protocol in wireless sensor networks," *Ad Hoc Netw.*, vol. 24, no. Part B, pp. 55–73, Jan. 2015.
- [12] R. K. Patro, "Localization in wireless sensor network with mobile beacons," in *Proc. 23rd IEEE Conv. Elect. Electron. Eng., Israel*, Sep. 2004, pp. 22–24.
- [13] Z. Zhong and T. He, "RSD: A metric for achieving range-free localization beyond connectivity," *IEEE Trans. Parallel Distrib. Syst.*, vol. 22, no. 11, pp. 1943–1951, Nov. 2011.
- [14] V. Vivekanandan and V. W. S. Wong, "Concentric anchor beacon localization algorithm for wireless sensor networks," *IEEE Trans. Veh. Technol.*, vol. 56, no. 5, pp. 2733–2744, Sep. 2007.
- [15] J. F. Huang, G. Y. Chang, and G. H. Chen, "A historical-beacon-aided localization algorithm for mobile sensor networks," *IEEE Trans. Mobile Comput.*, vol. 14, no. 6, pp. 1109–1122, Jun. 2015.
- [16] Y. Shang and W. Ruml, "Improved MDS-based localization," in *Proc. IEEE INFOCOM*, Mar. 2004, vol. 4, pp. 2640–2651.
- [17] D. Niculescu and B. Nath, "DV based positioning in ad hoc networks," *Telecommun. Syst.*, vol. 22, no. 1, pp. 267–280, Jan. 2003.
- [18] S. Kumar and D. K. Lobiyal, "An advanced DV-Hop localization algorithm for wireless sensor networks," *Wireless Pers. Commun.*, vol. 71, no. 2, pp. 1365–1385, Jul. 2013.
- [19] L. Gui, T. Val, and A. Wei, "Improving localization accuracy using selective 3-anchor DV-Hop algorithm," in *Proc. IEEE Veh. Technol. Conf.*, Sep. 2011, pp. 1–5.
- [20] G. Sharma and A. Kumar, "Improved DV-hop localization algorithm using teaching learning based optimization for wireless sensor networks," *Telecommun. Syst.*, vol. 67, no. 2, pp. 163–178, May 2017.
- [21] F. Shahzad, T. R. Sheltami, and E. M. Shakshuki, "DV-maxHop: A fast and accurate range-free localization algorithm for anisotropic wireless networks," *IEEE Trans. Mobile Comput.*, vol. 16, no. 9, pp. 2494–2505, Sep. 2017.
- [22] M. Sami, N. K. Noordin, M. Khabazian, F. Hashim, and S. Subramaniam, "A survey and taxonomy on medium access control strategies for cooperative communication in wireless networks: Research issues and challenges," *IEEE Commun. Surv. Tut.*, vol. 18, no. 4, pp. 2493–2521, Fourth Quarter 2016.
- [23] A. N. Alvi, S. H. Bouk, S. H. Ahmed, M. A. Yaqub, M. Sarkar, and H. Song, "Best-MAC: Bitmap-assisted efficient and scalable TDMA-based WSN MAC protocol for smart cities," *IEEE Access*, vol. 4, pp. 312–322, Jan. 2016.
- [24] X. Jiang and D. H. C. Du, "PTMAC: A prediction-based TDMA MAC protocol for reducing packet collisions in vanet," *IEEE Trans. Veh. Technol.*, vol. 65, no. 11, pp. 9209–9223, Nov. 2016.
- [25] Y. Zhang, Y. H. Lo, W. S. Wong, and F. Shu, "Protocol sequences for the multiple-packet reception channel without feedback," *IEEE Trans. Commun.*, vol. 64, no. 4, pp. 1687–1698, Apr. 2016.
- [26] A. A. Shaar, M. Gharib, and P. A. Davies, "Collision resolution in contention access local area networks using concatenated prime sequences," *IEE Proc. - Commun.*, vol. 149, no. 56, pp. 249–256, 2002.
- [27] W. S. Wong, "New protocol sequences for random-access channels without feedback," *IEEE Trans. Inf. Theory*, vol. 53, no. 6, pp. 2060–2071, Jun. 2007.
- [28] C. S. Chen, W. S. Wong, and Y. Q. Song, "Constructions of robust protocol sequences for wireless sensor and ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 57, no. 5, pp. 3053–3063, Sep. 2008.
- [29] K. W. Shum, C. S. Chen, C. W. Sung, and W. S. Wong, "Shift-invariant protocol sequences for the collision channel without feedback," *IEEE Trans. Inf. Theory*, vol. 55, no. 7, pp. 3312–3322, Jul. 2009.
- [30] K. W. Shum and W. S. Wong, "Construction and applications of CRT sequences," *IEEE Trans. Inf. Theory*, vol. 56, no. 11, pp. 5780–5795, Nov. 2010.

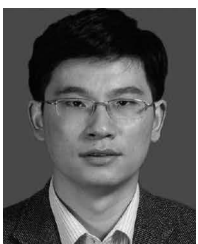
- [31] Y. Zhang, K. W. Shum, W. S. Wong, and F. Shu, "Binary sequences for multiple access collision channel: Identification and synchronization," *IEEE Trans. Commun.*, vol. 62, no. 2, pp. 667–675, Feb. 2014.
- [32] Y. Zhang, K. W. Shum, W. S. Wong, and F. Shu, "An energy-aware reliable deterministic broadcast protocol for wireless sensor networks," in *Proc. IEEE Globecom Workshops*, Dec. 2014, pp. 1427–1432.
- [33] Y. Zhang, Y.-H. Lo, S. Wang, and W. S. Wong, "A hybrid wavelength reservation scheme for large-scale optical networks," in *Proc. 25th Wireless Opt. Commun. Conf.*, May 2016, pp. 1–5.
- [34] K. W. Shum and W. S. Wong, "Construction of short protocol sequences with worst-case throughput guarantee," in *Proc. IEEE Int. Symp. Inf. Theory*, Jun. 2010, pp. 1828–1832.
- [35] *IEEE Standard for Information Technology—Local and Metropolitan Area Networks—Specific Requirements—Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (WPANS)* IEEE Std 802.15.4-2006 (Revision of IEEE Std 802.15.4-2003), pp. 1–320, Sep. 2006.



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