

Secure Position Verification for Wireless Sensor Networks in Noisy Channels

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Abstract. Position verification in wireless sensor networks (WSNs) is quite tricky in presence of attackers (malicious sensor nodes), who try to break the verification protocol by reporting their incorrect positions (locations) during the verification stage. In the literature of WSNs, most of the existing methods of position verification have used trusted verifiers, which are in fact vulnerable to attacks by malicious nodes. They also depend on some distance estimation techniques, which are not accurate in noisy channels (mediums). In this article, we propose a secure position verification scheme for WSNs in noisy channels without relying on any trusted entities. Our verification scheme detects and filters out all malicious nodes from the network with a very high probability.

Key words: Central limit theorems, Distributed protocol, Quantiles, Location verification, Security, Wireless networks.

1 Introduction

Secure position verification is important for wireless sensor networks (WSNs) because position of a sensor node is a critical input for many WSN applications those include tracking [11], monitoring [22] and geometry based routing [15]. Most of the existing position verification protocols rely on distance estimation techniques such as received signal strength (RSS)[1, 12], time of flight (ToF)[10] and time difference of arrival (TDoA)[19]. These techniques are relatively easy to implement, but they are a little bit expensive due to their requirement of special hardwares to estimate end-to-end distances. These above techniques, especially RSS techniques [1, 12] are perfect in terms of precision in *ideal* situations. The Friis transmission equation 1 [18] used in RSS techniques leads to this precision. But, in practice, due to the presence of noise in the network channel, signal attenuation does not necessarily follow this equation. There are many nasty effects those have influence on both propagation time and signal strength. So, the distance calculated using Friis equation usually differs from the actual distance. This difference, in reality, may also depend on the location of the sender and the receiver. A good position verification protocol should take care of these noises and limited precisions in distance estimation.

In this article, we use the RSS technique for position verification, where the receiving node estimates the distance of the sender on the basis of sending and

receiving signal strengths. Here we use the term *node* for wireless sensor device in WSNs, which is capable of processing power and equipped with transceivers communicating over a wireless channel. We consider that there are two types of nodes in the system, *genuine* nodes and *malicious* nodes. While the *genuine* nodes follow the implemented system functionality correctly, the *malicious* nodes are under the control of an adversary. To make the verification problem most difficult, we assume that the malicious nodes know all genuine nodes and their positions (coordinates). Once the coordinates of all genuine nodes are known, the main objective of a malicious node is to report a suitable faking position to all these genuine nodes such that it can deceive as many genuine nodes as possible. On the other hand, the objective of a genuine node is to detect the inconsistency in the information provided by a malicious node. In order to do this, they compare two different estimates of the distances, one calculated from the coordinates provided by a node and the other computed using the RSS technique. If these estimates are close, the genuine node accepts the sender as genuine, otherwise the sender node is considered as a malicious node. Malicious nodes, however, do not go for such calculations. They always report all genuine nodes as malicious and all malicious nodes as genuine to break the verification protocol. In this present work, we deal with such situations and discuss how to detect and filter out all such malicious nodes from a WSN in a noisy channel.

Related Works: Most of the existing methods for secure position verification [4, 5, 16, 17] rely on a fixed set of *trusted* entities (or *verifiers*) and distance estimation techniques to filter out faking (malicious) nodes. We refer to this model as the *trusted sensor* (or *TS*) model. In this model, faking nodes may use some modes of attacks that cannot be adopted by genuine nodes, such as radio signal jamming or using directional antenna that permit to implement attacks, *e.g.*, wormhole attack [13, 21] and Sybil attack [7]. Lazos and Poovendran [16] proposed a secure range-independent localization scheme, which is resilient to wormhole and Sybil attacks with high probability. Lazos *et. al.* [17] further refined this scheme with multi-lateration to reduce the number of required locators, while maintaining probabilistic guarantees. Shokri *et. al.* [21] proposed a secure neighbor verification protocol, which is secure against the classic 2-end wormhole attack. These authors assumed that there is no compromise between external adversaries and the correct nodes or their cryptographic keys, but these adversaries control a number of relay nodes which results in a wormhole attack. The TS model was also considered by Capkun and Hubaux [4] and Capkun *et. al.* [5]. In [4], the authors presented a protocol, which relies on the distance bounding technique proposed by Brands and Chaum [2]. The protocol presented in [5] relies on a set of hidden verifiers. There are two major weakness of the TS model; firstly, it is not possible to self-organize a network in a completely distributed way, and secondly, periodical checking is required to ensure that the trusted nodes remain trusted. Position verification problem becomes more challenging in the case of without providing any trusted sensor nodes prior. Delaët *et. al.*[6] considered the model as the *no trusted sensor* (or *NTS*) model. Hwang *et. al.*[14] and Delaët *et. al.*[6] have investigated the verification problem with the NTS model. In both

of these articles, the authors considered the problem, where the faking nodes operate synchronously with other nodes. The approach in [14] is randomized and consists of two phases: distance measurement and filtering. In the distance measurement phase, all nodes measure their distances from their neighbours, when faking nodes are allowed to corrupt the distance measure technique. In this phase, each node announces one distance at a time in a round robin fashion. Thus the message complexity is $O(n^2)$. In the filtering phase, each genuine node randomly picks up two so-called *pivot* nodes and carries out its analysis based on those pivots. However, these chosen pivot sensors could be malicious. So, the protocol may only give a probabilistic guarantee. The approach in [6] is deterministic and consists of two phases that can correctly filter out malicious nodes, which are allowed to corrupt the distance measure technique. In the case of RSS, the protocol tolerates at most $\lfloor \frac{n}{2} \rfloor - 2$ faking sensors (n being the total number of nodes in the WSN) provided no four sensors are located on the same circle and no four sensors are co-linear. In the case of ToF, it can handle up to $\lfloor \frac{n}{2} \rfloor - 3$ faking sensors provided no six sensors are located on the same hyperbola and no six sensors are co-linear.

Our results: The main contribution of this article is SECURENEIGHBORDISCOVERY, a secure position verification protocol in the NTS model in a noisy channel. To the best of our knowledge, this is the first protocol in the NTS model in a noisy environment. The protocol guarantees that the genuine nodes reject all incorrect positions of malicious nodes with very high probability (almost equal to 1) when there are sufficiently many genuine nodes in the WSN. If the noise in the network channel is negligible, this required number of genuine nodes matches with the findings of [6], where the authors proposed a deterministic algorithm for detecting faking sensors. However, when the noise is not negligible, each node can only have a limited precision for distance estimation. In such cases, it is not possible to develop a deterministic algorithm. Our protocol based on probabilistic algorithm takes care of this problem and filters out all malicious nodes from the WSN with a very high probability. When the number of nodes in the WSN is reasonably large, this probability turns out to be very close to 1. So, for all practical purposes, this proposed probabilistic method behaves almost like a deterministic algorithm. Our SECURENEIGHBORDISCOVERY protocol can be used to prevent Sybil attack [7] by verifying whether each message contains the real position (id) of its sender or not. The genuine nodes never accept any message with a malicious sender location.

2 Technical preliminaries

We assume that each node knows their geographic position (coordinates) and form complete graph for communication among themselves, i.e., each node is able to communicate with all other nodes in the WSN. We further assume that the WSN is partially synchronous: all nodes operate in phases. In *first phase*, each node is able to send exactly one message to all other nodes without collision. Unless mentioned otherwise, we will also assume that, for each transmission,

all nodes use the same transmission power S^s . Malicious nodes are allowed to transmit incorrect coordinates (incorrect identifier) to all other nodes. We further assume that malicious nodes cooperate among themselves in an omniscient manner (*i.e.* without exchanging messages) in order to deceive the genuine nodes in the WSN. Each malicious node obeys synchrony and transmits at most one message at the beginning of first phase and one message at the end of it.

Let d_{ij} be the true distance of node i from a genuine node j . Since node j does not know the location of node i , it estimates d_{ij} using two different techniques, one using the RSS technique and the other using the co-ordinates provided by node i . These two estimates are denoted by \hat{d}_{ij} and \tilde{d}_{ij} , respectively. In the RSS technique, under *idealized* conditions, node j can precisely measure the distance of node i using Friis transmission equation 1 [18] given by

$$S_{ji}^r = S_i^s \left(\frac{\lambda}{4\pi d_{ij}} \right)^2 \quad (1)$$

where S_i^s is the transmission power of the sender node i (here $S_i^s = S^s$ for all i), S_{ji}^r is the corresponding RSS at the receiving node j , and λ is the wave length.

If the sender node i gives perfect information regarding its location (*i.e.*, $\tilde{d}_{ij} = d_{ij}$), then the distance estimated using the RSS technique (\hat{d}_{ij}) and that computed from coordinates provided by node i (\tilde{d}_{ij}) will be equal in the ideal situation. However, in practice, when we have noise in the channel, they cannot match exactly, but they are expected to be close. But, if node i sends an incorrect information about its location, $|\tilde{d}_{ij} - \hat{d}_{ij}|$ can be large.

3 RSS technique in a noisy medium

The above Friis transmission equation 1 is used in telecommunications engineering, and gives the power transmitted from one antenna to another under *idealized* conditions. One should note that in the presence of noise in the network, the transmission equation may not hold, and it needs to be modified. Modifications to this equation based on the effects of impedance mismatch, misalignment of the antenna pointing and polarization, and absorption can be incorporated using an additional noise factor ε , which is supposed to follow a Normal (Gaussian) distribution with mean 0 and variance σ^2 . The modified equation is given by

$$S_{ji}^r = S_i^s \left(\frac{\alpha}{d_{ij}} \right)^2 + \varepsilon_{ij} \quad (2)$$

Where $\varepsilon_{ij} \sim N(0, \sigma^2)$ and $\alpha = \frac{\lambda}{4\pi}$. However, the ε_{ij} s are unobserved in practice. So, the receiving node j estimates the distance d_{ij} using the Friis transmission equation 1, and this estimate is given by $\hat{d}_{ij} = \alpha (S_i^s / S_{ji}^r)^{1/2}$. Since $\varepsilon_{ij} \sim N(0, \sigma^2)$, following the 3σ limit, S_{ji}^r is expected to lie between $S_i^s (\alpha/d_{ij})^2 - 3\sigma$ and $S_i^s (\alpha/d_{ij})^2 + 3\sigma$, where d_{ij} is the unknown true distance. Accordingly, \hat{d}_{ij} is expected to lie in the range $[d_{ij} \{1 + (3\sigma d_{ij}^2 / \alpha^2 S_i^s)\}^{-\frac{1}{2}}, d_{ij} \{1 - (3\sigma d_{ij}^2 / \alpha^2 S_i^s)\}^{-\frac{1}{2}}]$.

So, if the sender sends its genuine coordinates (i.e., $\tilde{d}_{ij} = d_{ij}$), \hat{d}_{ij} is expected to lie in the range $[\tilde{d}_{ij}\{1 + (3\sigma\tilde{d}_{ij}^2/\alpha^2 S_i^s)\}^{-\frac{1}{2}}, \tilde{d}_{ij}\{1 - (3\sigma\tilde{d}_{ij}^2/\alpha^2 S_i^s)\}^{-\frac{1}{2}}]$ with probability almost equal to 1 ($\simeq 0.9973$). The receiver node j accepts node i as genuine when \hat{d}_{ij} lies in that range. Throughout this article, we will assume σ^2 to be known. However, if it is unknown, one can estimate it by sending signals from known distances and measuring the deviations in received signal strengths from those expected in ideal situations. Looking at the distribution of these deviations, one can also check whether the error distribution is really normal (see [20] for the test of normality of error distributions). If it differs from normality, one can choose a suitable model for the error distribution and find the acceptance interval using the quantiles of that distribution. For the sake of simplicity, throughout this article, we will assume the error distribution to be normal, which is the most common and popular choice in the statistics literature.

We assume that there are n sensor nodes deployed over a region \mathcal{D} in a two dimensional plane, n_0 of them are genuine, and the rest n_1 ($n_0 + n_1 = n$) are malicious. Though our protocol does need n_0 and n_1 to be specified, for the better understanding of the reader, we will use these two terms for the description and mathematical analysis of our protocol.

3.1 Optimal strategy for malicious sensor nodes

Here, we deal with the situation, where all malicious nodes know all genuine nodes and their positions, or in other words, they know which of the sensor nodes are genuine and which ones are malicious. Therefore, to break the verification protocol, each malicious node reports all genuine nodes as malicious and all malicious nodes as genuine. In addition to that, a malicious node tries to report a suitable faking position so that it can deceive as many genuine nodes as possible. Let $\mathbf{x}_j = (x_j, y_j)$ $j = 1, 2, \dots, n_0$, be the coordinates of the genuine nodes and $\mathbf{x}_0 = (x_0, y_0)$ be the true location of a malicious node. Instead of reporting its original position, the malicious node looks for a suitable faking position $\mathbf{x}_f = (x_f, y_f)$ to deceive the genuine nodes. Note that if it sends \mathbf{x}_f as its location, from that given coordinates, the j -th ($j = 1, 2, \dots, n_0$) genuine node estimates its distance by $\tilde{d}_{0j} = \|\mathbf{x}_j - \mathbf{x}_f\|$, where $\|\cdot\|$ denotes the usual Euclidean distance. Again, the distance estimated from the received signal is $\hat{d}_{0j} = \alpha (S_0^s/S_{j0}^r)^{1/2}$. So, the j -th node accepts the malicious node as genuine if \hat{d}_{0j} will lies between $\alpha_{1,0j} = \tilde{d}_{0j}\{1 + (3\sigma\tilde{d}_{0j}^2/\alpha^2 S_{s,0})\}^{-1/2}$ and $\alpha_{2,0j} = \tilde{d}_{0j}\{1 - (3\sigma\tilde{d}_{0j}^2/\alpha^2 S_{s,0})\}^{-1/2}$. Now from equation 2, it is easy to check that $\alpha_{1,0j} \leq \hat{d}_{0j} \leq \alpha_{2,0j} \Leftrightarrow \alpha_{1,0j}^* = \alpha^2 S_0^s[1/\alpha_{2,0j}^2 - 1/\hat{d}_{0j}^2] \leq \varepsilon_{0j} \leq \alpha_{2,0j}^* = \alpha^2 S_0^s[1/\alpha_{1,0j}^2 - 1/\hat{d}_{0j}^2]$. Let p_{0j}^f be the probability that the malicious node, which is originally located at \mathbf{x}_0 , is accepted by the j -th genuine node when it reports \mathbf{x}_f as its location. Now, from the above discussion, it is quite clear that p_{0j}^f ($j = 1, 2, \dots, n_0$) is given by

$$p_{0j}^f = P \left[\hat{d}_{0j} \in (\alpha_{1,0j}, \alpha_{2,0j}) \right] = \frac{1}{\sigma\sqrt{2\pi}} \int_{\alpha_{1,0j}^*}^{\alpha_{2,0j}^*} \exp \left(-\frac{x^2}{2\sigma^2} \right) dx \quad (3)$$

Naturally, the malicious node tries to cheat as many genuine nodes as possible. Let us define an indicator variable Z_{0j}^f that takes the value 1 (or 0) if the malicious nodes successfully cheats (or fails to cheat) the j -th genuine node when it sends the faked location \mathbf{x}_f . Clearly, here $E(Z_{0j}^f) = P(Z_{0j}^f = 1) = p_{0j}^f$. So, given the coordinates of the genuine nodes $\mathcal{X}_0 = \{\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_{n_0}\}$, $\theta_{0,n_0}^{f,\mathcal{X}_0} = E(\sum_{j=1}^{n_0} Z_{0j}^f) = \sum_{j=1}^{n_0} p_{0j}^f$ denotes the expected number of genuine nodes to be deceived by the malicious node if it pretends \mathbf{x}_f as its location. Naturally, the malicious tries to find a faked position \mathbf{x}_f that maximizes $\theta_{0,n_0}^{f,\mathcal{X}_0}$. Let us define $\theta_{0,n_0}^{\mathcal{X}_0} = \sup_{\mathbf{x}_f \in \mathcal{F}_0} \theta_{0,n_0}^{f,\mathcal{X}_0}$, where \mathcal{F}_0 is the set of all possible faking coordinates. A malicious node located at \mathbf{x}_0 always looks for $\mathbf{x}_f \in \mathcal{F}_0$ such that $\theta_{0,n_0}^{f,\mathcal{X}_0} = \theta_{0,n_0}^{\mathcal{X}_0}$.

Here one should note that the region \mathcal{F}_0 depends on the true location of the malicious node \mathbf{x}_0 , and it is not supposed to contain any point lying in a small neighborhood \mathbf{x}_0 . Because in that case, \mathbf{x}_0 and \mathbf{x}_f will be almost the same, and the malicious node will behave almost like a genuine node. Naturally, the malicious node would not like to do that, and it will keep the neighborhood outside \mathcal{F}_0 . The size of this neighborhood of course depends on the specific application, and the value of $\theta_{0,n_0}^{\mathcal{X}_0}$ may also depend on that.

3.2 Optimal strategy for genuine sensor nodes

Let A_0 as the total number of nodes in the WSN that accept the malicious node located at \mathbf{x}_0 (as discussed in Section 3.1) as genuine. Since a malicious node is always accepted by other malicious nodes, if there are n_0 genuine nodes in the WSN and \mathcal{X}_0 denotes their co-ordinates, for the optimum choice of the faking coordinates \mathbf{x}_f , the (conditional) expected value of A_0 is given by $E(A_0 | n_0, \mathcal{X}_0) = (n - n_0) + \theta_{0,n_0}^{\mathcal{X}_0}$. Now, a genuine node does not know a priori how many genuine nodes are there in the WSN, and where they are located. So, at first, for a given n_0 , it computes the average of $E(A_0 | n_0, \mathcal{X}_0)$ over all possible \mathcal{X}_0 . If \mathcal{D} denotes the deployment region (preferably a convex region) for the sensor nodes, and if the nodes are assumed to be uniformly distributed over \mathcal{D} , this average is given by $E(A_0 | n_0) = \int_{\mathcal{X}_0 \in \mathcal{D}^{n_0}} E(A_0 | n_0, \mathcal{X}_0) \psi(\mathcal{X}_0) d\mathcal{X}_0$, where ψ is the uniform density function on \mathcal{D}^{n_0} . Here we have chosen ψ to be uniform because it is the most simplest one to deal with, and it is also the most common choice in the absence of any prior knowledge on the distribution of nodes in \mathcal{D} . When we have some prior knowledge about this distribution, ψ can be chosen accordingly. Now, define $\theta_{0,n_0} = \int_{\mathcal{X}_0 \in \mathcal{D}^{n_0}} \theta_{0,n_0}^{\mathcal{X}_0} \psi(\mathcal{X}_0) d\mathcal{X}_0$. Clearly, $E(A_0 | n_0) = (n - n_0) + \theta_{0,n_0}$ depends on n_0 , which is unknown to the genuine node. So, it finds an upper bound for $E(A_0 | n_0)$ assuming that at least half of the sensor nodes in the WSN are genuine. Under this assumption, this upper bound is given by $\lfloor 0.5n \rfloor + \theta_{0,\lfloor 0.5n \rfloor}$.

Theorem 1. *If there are n nodes in a WSN, and at least half of them are genuine, the expected number of acceptance for a malicious node located at $\mathbf{x}_0 = (x_0, y_0)$ cannot exceed $\lfloor 0.5n \rfloor + \theta_{0,\lfloor 0.5n \rfloor}$.*

Proof. Suppose there are n_0 genuine nodes (and $n_1 = n - n_0$ malicious nodes) in the WSN, where $n_0 > \lceil n/2 \rceil$. Define $\mathcal{X}_0 = \{\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_{n_0}\}$ and $\mathcal{X} = \{\mathbf{x}_1, \mathbf{x}_2, \dots,$

$\mathbf{x}_{\lceil n/2 \rceil} \} \subset \mathcal{X}_0$. Now, for given \mathcal{X}_0 , the expected number of acceptance for the malicious node located at \mathbf{x}_0 is $E(A_0 \mid n_0, \mathcal{X}_0) = \sup_{f \in \mathcal{F}_0} \left(\sum_{i=1}^{n_0} p_{0i}^f \right) + (n - n_0) \leq \sup_{f \in \mathcal{F}_0} \left(\sum_{i=1}^{\lceil n/2 \rceil} p_{0i}^f \right) + \sup_{f \in \mathcal{F}_0} \left(\sum_{i=\lceil n/2 \rceil+1}^{n_0} p_{0i}^f \right) + (n - n_0) \leq E(A_0 \mid \lceil n/2 \rceil, \mathcal{X}) + (n_0 - \lceil n/2 \rceil) + (n - n_0) = \theta_{0, \lceil n/2 \rceil}^{\mathcal{X}} + (n - \lceil n/2 \rceil)$. Now, taking expectation w.r.t. \mathcal{X}_0 , we get $E(A_0 \mid n_0) \leq \theta_{0, \lceil 0.5n \rceil} + \lfloor n/2 \rfloor$. \square

Note that $\theta_{0, \lceil 0.5n \rceil}$ and the upper bound depend on the location of the malicious node \mathbf{x}_0 . So, for a genuine node, it is an unknown random quantity. Therefore, a genuine node takes a conservative approach and computes $\theta_{\lceil n/2 \rceil}^* = \lceil \sup_{\mathbf{x}_0 \in \mathcal{D}} \theta_{0, \lceil n/2 \rceil} \rceil$. Note that here, $\theta_{\lceil n/2 \rceil}^*$ gives an upper bound of the expected number of genuine nodes to be deceived by a malicious node in \mathcal{D} when there are $\lceil n/2 \rceil$ genuine sensor nodes in the WSN. To filter out all malicious nodes from the WSN, a genuine node follows the idea of [6]. For any node, it calculates the total number of acceptances (approvals) (A) and rejections (accusations) (R), and considers the node as malicious if R exceeds $A - \theta_{\lceil n/2 \rceil}^*$. Since $A + R = n$, a node is considered to be genuine if $A \geq (n + \theta_{\lceil n/2 \rceil}^*)/2$. Note that if there are n_0 genuine nodes and n_1 malicious nodes in the WSN, a malicious node, on an average, can be accepted by at most $\theta_{n_0}^* + n_1$ nodes, and it will be rejected by at least $n_0 - \theta_{n_0}^*$ nodes. So, for a malicious node $A - R - \theta_{\lceil n/2 \rceil}^*$ is expected to be smaller than $(n_1 + 2\theta_{n_0}^*) - n_0 - \theta_{\lceil n/2 \rceil}^* \leq \lfloor n/2 \rfloor + \theta_{n_0}^* - n_0$ (from Theorem 1). Therefore, if we have $n_0 \geq \lfloor n/2 \rfloor + \theta_{n_0}^*$, all malicious nodes are expected to be filtered out from the WSN. A more detailed mathematical analysis of our protocol will be given in Section 5. For computing $\theta_{\lceil n/2 \rceil}^*$, a genuine node uses the statistical simulation technique [3] assuming that the sensors are distributed over \mathcal{D} with density ψ (which is taken to be uniform in this article). First it generates coordinates \mathbf{x}_0 for the malicious node and \mathcal{X} for $\lceil n/2 \rceil$ genuine nodes in \mathcal{D} to compute $\theta_{0, \lceil n/2 \rceil}^{\mathcal{X}}$ by maximizing $\theta_{0, \lceil n/2 \rceil}^{f, \mathcal{X}}$. Repeating this over several \mathcal{X} one gets $\theta_{0, \lceil n/2 \rceil}$ as an average of the $\theta_{0, \lceil n/2 \rceil}^{\mathcal{X}}$ s. This whole procedure is repeated for several random choices of \mathbf{x}_0 to compute $\theta_{\lceil n/2 \rceil}^* = \lceil \sup_{\mathbf{x}_0 \in \mathcal{D}} \theta_{0, \lceil n/2 \rceil} \rceil$. Note that this is an offline calculation, and it has to be done once only.

4 The Protocol

Based on above discussions, we develop the SECURENEIGHBORDISCOVERY protocol. It is a *two-phase* approach to filter out malicious nodes. The *first phase* is named as ACCUSEAPPROVE, and the *second phase* is named as FILTERING.

In the *first phase*, each sensor node reports its coordinates to all other nodes by transmitting an initial message. Next, for each pair of nodes i and j , node j computes two estimates of the distance d_{ij} , one using the RSS technique (\hat{d}_{ij}) and the other from the reported coordinates (\tilde{d}_{ij}), as mentioned earlier. If $\hat{d}_{ij} \notin (\alpha_{1,ij}, \alpha_{2,ij})$ then node j accuses node i for its faking position. Otherwise, node j approves the location of node i as genuine. Here $\alpha_{1,ij} = \tilde{d}_{ij} \{1 + (3\sigma \tilde{d}_{ij}^2 / \alpha^2 S_{s,i})\}^{-\frac{1}{2}}$ and $\alpha_{2,ij} = \tilde{d}_{ij} \{1 - (3\sigma \tilde{d}_{ij}^2 / \alpha^2 S_{s,i})\}^{-\frac{1}{2}}$ are

analogues of $\alpha_{1,0j}$ and $\alpha_{2,0j}$ defined in Section 3.1. To keep track of these accusations and approvals, each node j maintains an array $accus_j$, and transmits it to all other nodes at the end of this phase. So, in the *first phase*, each node j executes the ACCUSEAPPROVE protocol which is given below.

<p>Protocol: ACCUSEAPPROVE (executed by node j)</p> <ol style="list-style-type: none"> 1. j exchanges coordinates by transmitting $init_j$ & receiving $n - 1$ $init_i$. 2. for each received message $init_i$: 3. compute \hat{d}_{ij} using the ranging (RSS) technique and \tilde{d}_{ij} using the reported coordinates of i. 4. if $[\hat{d}_{ij} \notin (\alpha_{1,ij}, \alpha_{2,ij})]$ then $accus_j[i] \leftarrow true$ else $accus_j[i] \leftarrow false$ 5. j exchanges accusations by transmitting $accus_j$ & receiving $n - 1$ $accus_i$.
<p>Protocol: FILTERING (executed by node j)</p> <ol style="list-style-type: none"> 1. $F = \phi$, $G = \{1, 2, \dots, n\}$, $n' \leftarrow n$ 2. repeat $\{k \leftarrow n'\}$ 3. for each received $accus_i$: ($i \in G$) 4. for each r: ($r \in G$) 5. if $accus_i[r] = true$ then $NumAccus_r + = 1$ else $NumApprove_r + = 1$ 6. $newF = \phi$. 7. for each sensor i: ($i \in G$) 8. if $(NumApprove_i \geq (k + \theta_{\lceil n/2 \rceil}^*)/2)$ then j considers i as a genuine node. else j considers i as a malicious node. filter out i, $newF = newF \cup \{i\}$, $n' \leftarrow n' - 1$. 9. $F = F \cup newF$, $G = G \setminus newF$. 10. for each sensor i: ($i \in newF$) 11. discard $accus_i$ & corresponding i^{th} entry of $accus_r$ for all $r \in G$ 12. } until $(k \neq n')$

In the *second phase*, each node j executes the FILTERING protocol, where it counts the number of accusations and approvals toward node i including its own message. Node j finds node i as malicious if the number of accusations exceeds the number of approvals minus $\theta_{\lceil n/2 \rceil}^*$. Conversely, node i is considered as genuine if its number of approvals is greater than or equal to $(n + \theta_{\lceil n/2 \rceil}^*)/2$. In this process, nodes that are detected as malicious nodes, are filtered out from the WSN. Next, it ignores the decisions given by these deleted nodes and repeats the same filtering method with the remaining ones. If there are n' nodes in the WSN, a node is considered to be malicious if the number of approvals is smaller than $(n' + \theta_{\lceil n'/2 \rceil}^*)/2$. Instead of $\theta_{\lceil n/2 \rceil}^*$, we can use $\theta_{\lceil n'/2 \rceil}^*$, but in that case, $\theta_{\lceil n'/2 \rceil}^*$ needs to be computed again, and it needs to be computed online. Therefore, to reduce the computing cost of our algorithm, here we stick to $\theta_{\lceil n/2 \rceil}^*$. Note that the use of $\theta_{\lceil n/2 \rceil}^*$ also makes the filtering protocol more strict in the sense that it

increases the probability of a node being filtered out. Node j repeats this method until there are no further deletions of nodes from the WSN.

The FILTERING protocol is given above. Here F and G denote the set of malicious and genuine nodes respectively. Initially, we set $F = \phi$ and $G = \{1, 2, \dots, n\}$. At each stage, we detect some malicious nodes and filter them out. Those nodes are deleted from G and included in F . At the end of the algorithm, G gives the set of nodes remaining in WSN, which are considered to be genuine nodes. It would be ideal if the set of coordinates of the nodes in G matches with \mathcal{X} . However, it might not always be possible. The main objective of our protocol is to filter out all malicious nodes from the WSN. In the process, a few genuine nodes may also get removed. So, if not all, at the end of the algorithm, one would like G to contain most of the genuine nodes and no malicious nodes.

5 Correctness of the protocol

To check the correctness of the above protocol, we consider the worst case scenario as mentioned before, where all genuine nodes get accused by all malicious nodes, and each malicious node gets approved by all other malicious nodes. Assume that there are n_0 genuine nodes and n_1 malicious nodes in the WSN. Now, for $j, j' = 1, 2, \dots, n_0$, define the indicator variable $Z_{jj'}^* = 1$ if the j' -th genuine node accepts the j -th genuine node, and 0 otherwise. So, for the j -th genuine node, the number of approvals A_j^* can be expressed as $A_j^* = 1 + \sum_{j'=1, j' \neq j}^{n_0} Z_{jj'}^*$, where the $Z_{jj'}^*$ s are independent and identically distributed (*i.i.d.*) as Bernoulli random variables with the success probability $p = P(Z_{jj'}^* = 1) = 0.9973 \simeq 1$. If n_0 is reasonably large, using the Central Limit Theorem (CLT) [8] for the *i.i.d.* case, one can show that (see Theorem 2) $P(A_j^* \geq (n + \theta_{[n/2]}^*)/2) \simeq 1 - \Phi(\tau)$, where Φ = cumulative distribution function of the standard normal distribution and $\tau = \frac{n + \theta_{[n/2]}^* - 2n_0p}{2\sqrt{p(1-p)(n_0-1)}}$. Since this probability does not depend on j , the same expression holds for all genuine nodes.

Theorem 2. *Assume that there are n nodes in the WSN, and n_0 of them are genuine. If n_0 is sufficiently large, for the j -th genuine node ($j = 1, 2, \dots, n_0$), we have the acceptance probability $P\left(A_j^* \geq \frac{n + \theta_{[n/2]}^*}{2}\right) \simeq 1 - \Phi\left(\frac{n + \theta_{[n/2]}^* - 2n_0p}{2\sqrt{p(1-p)(n_0-1)}}\right)$.*

Proof. Since all malicious nodes are assumed to be intelligent, none of them will accept the genuine node. One should also notice that the j -th genuine node will always accept itself. So, for this node, it is easy to see that $A_j^* - 1 = \sum_{j'=1, j' \neq j}^{n_0} Z_{jj'}^*$ is the sum of $(n_0 - 1)$ independent Bernoulli random variables, each of which takes the values 1 and 0 with probability $p = 0.9973$ and $1 - p = 0.0027$, respectively. From the Central Limit Theorem (C.L.T.) for *i.i.d.* random variables [8], we have $\sqrt{n_0 - 1} \left(\frac{A_j^*}{n_0 - 1} - p\right) \sim N(0, p(1 - p))$. Therefore, the acceptance probability of the j -th node is $P\left(A_j^* \geq \frac{n + \theta_{[n/2]}^*}{2}\right) =$

$$P\left(\frac{A_j^* - 1}{n_0 - 1} \geq \frac{n + \theta_{\lceil n/2 \rceil}^* - 2}{2(n_0 - 1)}\right) \simeq 1 - \Phi\left(\frac{n + \theta_{\lceil n/2 \rceil}^* - 2 - 2(n_0 - 1)p}{\sqrt{2(n_0 - 1)p(1 - p)}}\right) \simeq 1 - \Phi\left(\frac{n + \theta_{\lceil n/2 \rceil}^* - 2n_0p}{2\sqrt{p(1 - p)(n_0 - 1)}}\right). \quad \square$$

If $n + \theta_{\lceil n/2 \rceil}^* - 2n_0p < 0$ (equivalent to $n_0 > (n + \theta_{\lceil n/2 \rceil}^*)/2$ since $p \simeq 1$), for any genuine node j ($j = 1, 2, \dots, n_0$), the acceptance probability $P(A_j^* \geq (n + \theta_{\lceil n/2 \rceil}^*)/2)$ is bigger than $1/2$. Again, if p is close to 1 (which is the case here), the denominator of τ becomes close to zero. So, in that case, the acceptance probability $P(A_j^* \geq (n + \theta_{\lceil n/2 \rceil}^*)/2)$ turns out to be very close to 1. Note that if we have $n_0 \geq \lfloor n/2 \rfloor + \theta_{n_0}^*$, the condition $n_0 > (n + \theta_{\lceil n/2 \rceil}^*)/2$ gets satisfied.

Now, given the coordinates of n_0 genuine sensor nodes \mathcal{X}_0 , the malicious node, which is actually located at \mathbf{x}_0 but sends \mathbf{x}_f as its faked location, has the number of acceptance $A_0 = n_1 + \sum_{j=1}^{n_0} Z_{0j}^f$, where n_1 is the number of malicious nodes in the WSN, and $Z_{0j}^f \sim B(1, p_{0j}^f)$ for $j = 1, 2, \dots, n_0$ (see Section 3.1). Again from the discussion in Section 3.2, it follows that $E(A_0) < n_1 + \theta_{n_0}^*$. So, if $n_0 \geq \lfloor n/2 \rfloor + \theta_{n_0}^*$, using Theorem 1, it is easy to check that $(n + \theta_{\lceil n/2 \rceil}^* - E(A_0)) > 0.5(n_0 - \lfloor n/2 \rfloor - \theta_{n_0}^*) \geq 0$, and it is expected to increase with n linearly. So, if the standard deviation of A_0 (square root of the variance $\text{Var}(A_0)$) remains bounded as a function of n , or it diverges at a slower rate (which is usually the case), for sufficiently large number of nodes in the WSN, the final acceptance probability of the malicious node $P(A_0 \geq (n + \theta_{\lceil n/2 \rceil}^*)/2)$ becomes very close to zero.

Theorem 3. *If we have sufficiently large number of nodes in the wireless sensor network and $n_0 \geq \lfloor n/2 \rfloor + \theta_{n_0}^*$, for any malicious node, the final acceptance probability $P(A_0 \geq (n + \theta_{\lceil n/2 \rceil}^*)/2) \simeq 0$.*

Proof. Define Y as the number of genuine nodes in the WSN that accept the malicious node as genuine. First note that $A_0 = n_1 + Y$, and Y can be expressed as $Y = \sum_{i=1}^{n_0} Y_i$, where the Y_i s are independent, and $Y_i \sim \text{Ber}(p_i)$, for the p_i s being the probabilities of acceptance by genuine nodes in WSN for the best choice of the faking position. Clearly, $E(Y) \leq \theta_{n_0}^*$, $\sigma_{n_0}^2 = \text{Var}(Y) = \sum_{i=1}^{n_0} p_i(1 - p_i)$ and $\rho_{n_0}^3 = \sum_{i=1}^{n_0} E|Y_i - E(Y_i)|^3 < \sigma_{n_0}^2$. Now, under the condition $n_0 \geq \lfloor n/2 \rfloor + \theta_{n_0}^*$, it is easy to check that $E(A_0) < (n + \theta_{\lceil n/2 \rceil}^*)/2$, and $(n + \theta_{\lceil n/2 \rceil}^*)/2 - E(A_0)$ increases with n linearly. So, if $\sigma_{n_0}^2 = \text{Var}(Y) = \text{Var}(A_0)$ remains bounded as a function of n , using Chebychev's inequality or otherwise, one can show that $\lim_{n \rightarrow \infty} P(A_0 \geq (n + \theta_{\lceil n/2 \rceil}^*)/2) = 0$. But the most likely case is $\sigma_{n_0}^2 \rightarrow \infty$ as $n \rightarrow \infty$. In this case, one can verify that $\rho_{n_0}/\sigma_{n_0} \rightarrow 0$ as $n \rightarrow \infty$ (or equivalently $n_0 \rightarrow \infty$). Therefore, from Liapunov's Central Limit Theorem [8], we have $[A_0 - E(A_0)]/\sqrt{\text{Var}(A_0)} \sim N(0, 1)$ and $P(A_0 \geq (n + \theta_{\lceil n/2 \rceil}^*)/2) \simeq 1 - \Phi\left(\frac{(n + \theta_{\lceil n/2 \rceil}^*)/2 - E(A_0)}{\sqrt{\text{Var}(A_0)}}\right)$. Now, $(n + \theta_{\lceil n/2 \rceil}^*)/2 - E(A_0)$ grows with n linearly, but $\sqrt{\text{Var}(A_0)} \leq \sqrt{n_0}/2$ grows at a slower rate. So, $P(A_0 \geq (n + \theta_{\lceil n/2 \rceil}^*)/2) \rightarrow 0$ as $n \rightarrow \infty$, and for large n , $P(A_0 \geq (n + \theta_{\lceil n/2 \rceil}^*)/2) \simeq 0$. Since the result does not depend on the location of the malicious node \mathbf{x}_0 , it holds for all malicious nodes present in the WSN. \square

Theorems 2 and 3 suggest that if n is sufficiently large and $n_0 \geq \lfloor n/2 \rfloor + \theta_{n_0}^*$, all genuine nodes in the WSN have acceptance probabilities close to 1, and all malicious nodes have acceptance probabilities close to 0. So, it is expected that after the first round of filtering, if not all, a large number of genuine nodes will be accepted. On the contrary, if not all, almost all malicious nodes will get filtered out from the network. However, for proper functioning of the WSN, one needs to remove all malicious nodes. In order to do that, we repeat the FILTERING procedure again with the remaining nodes. Now, among these remaining nodes, all but a few are expected to be genuine, and because of this higher proportion of genuine nodes, the acceptance probability of the genuine nodes are expected to increase, and those for the malicious nodes are expected to decrease further. So, if this procedure is used repeatedly, after some stage, WSN is expected to contain genuine nodes only, and no nodes will be filtered out after that. When this is the case, our FILTERING algorithm stops. Note that this algorithm does not need the values of n_0 and n_1 to be specified. We need to know n only for computation of $\theta_{\lfloor n/2 \rfloor}^*$. This is the only major computation involved in our method, but one can understand that this is an off-line calculation. If we know a priori the values of $\theta_{\lfloor n/2 \rfloor}^*$ for different n , one can use those tabulated values to avoid this computation. Note that the condition $n_0 \geq \lfloor n/2 \rfloor + \theta_{n_0}^*$ is only a sufficient condition under which the proposed protocol functions properly. Later, we will see that in the presence of negligible noise (or in the absence of noise) in the WSN, this condition matches with that of [6], and in that case, it turns out to be a necessary and sufficient condition. However, in other cases, it remains a sufficient condition only, and our protocol may work properly even when it is not satisfied. Our simulation studies in the next section will make this more clear.

6 Simulation results

We carried out simulation studies to evaluate the performance of our proposed algorithm. In the first part of the simulation, we calculated the value of $\theta_{\lfloor n/2 \rfloor}^*$ using the statistical simulation technique [3], and using that $\theta_{\lfloor n/2 \rfloor}^*$, in the second part, we filtered out all suspected malicious nodes from the WSN. While maximizing $\theta_{0, \lfloor n/2 \rfloor}^{f, \mathcal{X}}$ w.r.t. \mathbf{x}_f , in order to ensure that \mathbf{x}_f and \mathbf{x}_0 are not close, an open ball around \mathbf{x}_0 is kept outside the search region \mathcal{F}_0 . Unless mentioned otherwise, we carried out our experiments with 100 sensors nodes, but for varying choice of n_0 and n_1 and also for different levels of noise (i.e., different values of σ^2). For choosing the value of σ^2 , first we considered two imaginary nodes (the sender and the receiver nodes) located at two extreme corners of \mathcal{D} and calculated the received signal strength $S_{extreme}^r$ for that set up under ideal condition (see Friis equation 1). The error standard deviation σ was taken as smaller than or equal to $SS = S_{extreme}^r/3$ to ensure that all received signal strengths remain positive (after error contamination) with probability almost equal to 1.

6.1 WSN with insignificant noise ($\sigma = 10^{-6}SS$)

In this case, we observe that the value of $\theta_{0, \lceil n/2 \rceil}^{\mathcal{X}}$ remains almost constant and equal to $2p = 1.9946 \simeq 2$ for varying choices of \mathbf{x}_0 and \mathcal{X} . So, we have $\theta_{\lceil n/2 \rceil}^* = 2$. In fact, in this case, θ_k^* turns out to be 2 for all $k \geq 2$. So, if we choose $n_0 = 52$ and $n_1 = 48$, the condition $n_0 \geq \lceil n/2 \rceil + \theta_{n_0}$ gets satisfied, and one should expect the protocol to work well. When we carried out experiment, each of the 48 malicious nodes could deceive exactly two genuine nodes, and as a result, the number of approvals turned out to be 50. So, all of them failed to reach the threshold $(n + \theta_{\lceil n/2 \rceil}^*)/2 = 51$, and they were filtered out from the WSN at the very first round. On the contrary, all 52 genuine nodes had number of approvals bigger than (47 out of 52 nodes) or equal to (5 out of 52 nodes) 51, and none of them were filtered out. So, at the beginning of the second round of filtering, we had 52 nodes in the WSN, and all of them were genuine. Since the number of approvals for each genuine node remained the same as it was in the first round, it was well above the updated threshold $(52+2)/2=27$. So, no other nodes were filtered out, and our algorithm stopped with all genuine nodes and no malicious nodes in the network. Needless to mention that the proposed protocol led to the same result for all higher values of n_0 . But it did not work properly when we took $n_0 = 51$ and $n_1 = 49$. In that case, all malicious nodes had 51 approvals, and those for the genuine nodes were smaller than or equal to 51. So, no malicious nodes but some genuine nodes were deleted at the first round of filtering. As a result, the number of approvals for the genuine nodes became smaller at the second round, and that led to the removal of those nodes from the WSN. Note that in this case, the condition $n_0 \geq \lceil n/2 \rceil + \theta_{n_0}$ does not get satisfied. So, here the condition is not only sufficient, but it turns out to be necessary as well.

We carried out our experiment also with 101 nodes. When there were 51 genuine and 50 malicious nodes in the WSN, the protocol did not work properly. But in the case of $n_0 = 52$ and $n_1 = 49$, it could filter out all malicious nodes. In that case, each malicious node had 51 approvals, smaller than the threshold $(n + \theta_{\lceil n/2 \rceil}^*)/2 = 51.5$. But, 48 out of 52 genuine nodes were accepted by all 52 genuine nodes. So, at the end of first round of filtering, in the WSN, we had 48 genuine nodes only. Naturally, no other nodes were removed at the second round. Again this shows that $n_0 \geq \lceil n/2 \rceil + \theta_{n_0}$ is a necessary and sufficient condition for the protocol to work when the noise is negligible. This is consistent with the findings of [6], where the authors allowed no noise in the network.

6.2 WSN with significant noise ($\sigma = SS$)

Unlike the previous case, here $\theta_{0, \lceil n/2 \rceil}^{\mathcal{X}}$ did not remain constant for different choices of \mathbf{x}_0 and \mathcal{X} . Considering $n = 100$, we computed $\theta_{0, \lceil n/2 \rceil}^{\mathcal{X}}$ over 500 simulations, and they ranged between 5.9831 and 23.6964 leading to $\theta_{\lceil n/2 \rceil}^* = 24$ and $(n + \theta_{\lceil n/2 \rceil}^*)/2 = 62$. Clearly, if we start with less than 62 genuine nodes, the protocol fails as all genuine nodes get deleted at the first round of filtering. So, we started with 62 genuine and 38 malicious nodes. One can notice that here $n_0 < \lceil n/2 \rceil + \theta_{\lceil n/2 \rceil}^*$, and the condition $n_0 \geq \lceil n/2 \rceil + \theta_{n_0}^*$ does not get satisfied.

But our protocol worked nicely and filtered out all malicious nodes from the WSN. This shows that the above condition is only sufficient in this case. At the first round of filtering, 54 out of the 62 genuine nodes, and 5 out of 38 malicious nodes could reach the threshold. So, at the beginning of the second round, we had only 59 nodes in the network leading to a threshold of $(59+24)/2=41.5$. Naturally, none of the malicious nodes and all the genuine nodes could cross this threshold, and at the end of the second round of filtering, we had only 54 nodes in the WSN, all of which were genuine. As expected, no nodes were filtered out at the third round, and our algorithm terminated with 54 genuine nodes.

6.3 A modified filtering algorithm based on quantiles

Note that in the previous problem, if we start with 60 genuine nodes and 40 malicious nodes, the protocol fails as all genuine nodes get deleted at the first round of filtering. Here we propose a slightly modified version of our protocol that works even when n_0 is smaller than $(n + \theta_{\lceil n/2 \rceil}^*)/2$. Instead of using $(n + \theta_{\lceil n/2 \rceil}^*)/2$, we use a sequence of thresholds based on different quantiles of $\theta_{0, \lceil n/2 \rceil}^{\mathcal{X}}$. At first, we begin with the threshold $n/2$ (i.e. replace $\theta_{\lceil n/2 \rceil}^*$ by 0) and follow the protocol described in Section 4. In the process, some nodes may get filtered out. If there are $n^{(1)}$ nodes remaining in the WSN, we use the threshold $(n^{(1)} + \theta_{\lceil n/2 \rceil}^{0.1})/2$ (i.e. replace $\theta_{\lceil n/2 \rceil}^*$ by $\theta_{\lceil n/2 \rceil}^{0.1}$) and apply the filtering phase of the protocol FILTERING on the remaining nodes. Here $\theta_{\lceil n/2 \rceil}^q$ denotes the q -th ($0 < q < 1$) quantile of $\theta_{0, \lceil n/2 \rceil}^{\mathcal{X}}$, and this can be estimated from the 500 values of $\theta_{0, n/2}^{\mathcal{X}}$ observed during simulation. This procedure is repeated with thresholds $(n^{(i)} + \theta_{\lceil n/2 \rceil}^{i/10})/2$ for $i = 2, 3, \dots, 9$, and finally we use the threshold $(n^{(10)} + \theta_{\lceil n/2 \rceil}^*)/2$. The nodes remaining in the WSN after these 11 steps of filtering are considered as genuine nodes. This algorithm worked well in our case, and it filtered out all malicious nodes from the WSN without losing a single genuine node. In fact, all malicious nodes were filtered out after the first two steps, and there were no deletions of nodes after that. The results for the first two steps are shown in Table 1 (in our case, $\theta_{\lceil n/2 \rceil}^{0.1}$ was 8.6786). The total number of approvals for the deleted nodes are also reported in the table for better understanding of the algorithm.

This modified version could filter out up to 44 malicious nodes. In the case of $n_0 = 56$ and $n_1 = 44$, only one genuine node was deleted from the WSN before all malicious nodes were filtered out. However, in the case of $n_0 = 55$, $n_1 = 45$ our algorithm failed. In that case, all genuine nodes had 54 or 55 approvals, but almost all malicious nodes had more than 55 approvals. So, our protocol could remove only 9 malicious nodes before all genuine were filtered out.

7 Possible improvements

In this article, we have used the modified version of Friis transmission equation 2 for developing our SECURENEIGHBORDISCOVERY protocol. However, sometimes one needs empirical adjustments to the basic Friis equation 1 using larger

Table 1. First two steps of filtering (based on quantiles) with $n_0 = 60$ and $n_1 = 40$.

Step(i)	Total nodes ($n^{(i)}$)		Threshold	Nodes deleted		No. of approvals for deleted nodes
	Genuine	Malicious		Genuine	Malicious	
0	60	40	50.00	0	1	< 50
	60	39	49.50	0	0	—
1	60	39	53.84	0	3	51-54
	60	36	52.34	0	5	55-56
	60	31	49.84	0	5	57-58
	60	26	47.34	0	17	59-61
	60	9	38.84	0	9	62-69
	60	0	34.34	0	0	—

exponents. These are used in terrestrial models, where reflected signals can lead to destructive interference, and foliage and atmospheric gases contribute to signal attenuation [9]. There one can consider S_{ji}^r/S_i^s to be proportional to $G_r G_s (\lambda/d_{ij})^m$, where G_r and G_s are mean effective gain of the antennas and m is a scalar typically lies in the range [2, 4]. If m is known, one can develop a verification scheme following the method described in this article. Even if it is not known, it can be estimated by sending signals from known distances and measuring the received signal strengths.

However, our proposed protocol is not above all limitations. In this article, we have assumed that the underlying network topology is a complete graph. But, in practice, this may not always be the case. In multi-hop network topology, our SECURENEIGHBORDISCOVERY protocol based on voting can be used in the neighborhood of each node, provided there are sufficiently many genuine nodes in the neighborhood. However, the performance of this verification protocol in the case of multi-hop network topology needs to be thoroughly investigated.

8 Concluding remarks

In this article, we have proposed a distributed secure position verification protocol for WSNs in noisy channels. In this approach, without relying on any trusted sensor nodes, all genuine nodes detect the existence of malicious nodes and filter them out with a very high probability. The proposed method is conceptually quite simple, and it is easy to implement if $\theta_{\lceil n/2 \rceil}^*$ is known. Calculation of $\theta_{\lceil n/2 \rceil}^*$ is the only major computation involved in our method, but one should note that this is an off-line calculation.

In the case of negligible noise in the WSN, we have seen that the performance of our protocol matches with that of the deterministic methods of [6]. However, when the noise is not negligible, each of the sensor nodes can only have a limited precision for distance estimation. In such cases, it is not possible to develop a deterministic algorithm [6]. Our protocol based on probabilistic algorithm takes care of this problem, and it filters out all malicious nodes with very high probability. When the number of nodes in the WSN is reasonable large, this probability turns out to be very close to 1. So, for all practical purposes, our

proposed method behaves almost like a deterministic algorithm as we have seen in Section 6. Since the influence of noise on signal propagation is very common in WSNs, this probabilistic approach is very practical for the implementation perspective in the real world.

One should also notice that compared to the randomized protocol of Hwang *et al.* [14], our protocol leads to substantial savings on the time and the power used for transmissions. In [14], the message complexity is $O(n^2)$, since each sensor announces one distance at a time in a round robin fashion. But, in the case of our proposed protocol, $O(n)$ messages are transmitted in the first phase, and each sensor announces all distances through a single message.

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