Chapter 6

CONCLUSION

This investigation studied localisation systems and the different categories of position-discovery algorithms. On the basis of this study, the following approaches were employed to design a novel localisation algorithm: beacon-based, incremental, fine-grained, distributed, successive-refinement approaches, using a subset of references. Incorporating these approaches greatly improves the performance of the localisation algorithm, achieving several design objectives and suitability for WSNs.

Information fusion plays a critical role in WSNs. Therefore, the possibility of integrating information fusion into the localisation algorithm was studied. It was found that the best way to achieve this goal was to use a localised algorithm, which is a special type of distributed algorithm in which only a subset of nodes is involved in the position discovery process. This integration helped the proposed localisation algorithm to achieve two main goals simultaneously: location discovery, and the main objectives of information fusion, which are the improvement of accuracy and saving energy.

To achieve the above integration, a novel localisation algorithm, called ALWadHA, was proposed. ALWadHA is based on a smart reference-selection method that is able to select the best subset of references. The selected subset consists of the references that are most likely to contribute to accurate position computation of an unknown. The proposed algorithm was implemented and evaluated using simulation. Several experiments were conducted to evaluate the performance of ALWadHA, using criteria such as accuracy of estimation, number of references used and energy efficiency. The information fusion properties of the proposed scheme were analysed and several techniques used to make information fusion play a leading role were discussed.

The technique used by the proposed scheme to make it resistant to malicious attacks was also investigated.

The hypothesis of this study was that a *localisation algorithm can rely on using a low number of references to achieve an accurate estimation without compromising the simplicity, security, robustness or the energy efficiency of the algorithm.*

6.1 CONCLUSIONS

Most of the existing localisation algorithms rely on using a high number of references to estimate the position of nodes. On the one hand, this approach could enhance the accuracy of estimation. On the other hand, it has several drawbacks, especially for resource-constrained WSNs. Using a high number of references requires more computations and more memory space and consumes more energy. Therefore, this approach could be infeasible for resource-constrained WSNs. Moreover, the availability of a high number of references is a critical issue that cannot be guaranteed in WSNs. In a hostile environment, excluding malicious references would lead to more accurate estimation than using all the available references. In a noisy environment, nodes could enhance the accuracy of estimation if they exclude those references with high distance-measurement error that could bias the estimation toward an inaccurate location.

Using only a subset of references with a chance of higher accuracy could help to overcome the problems associated with using all the available references. Moreover, following this approach (i.e., using a subset of references) will help to achieve several design objectives, such as accuracy, robustness, simplicity, security, localisation and energy efficiency. However, selecting a subset of references is not an easy task or a straightforward technique that can simply be applied by selecting a low number of references. For instance, the technique proposed by the authors of [37] is based on selecting the nearest three references as a subset. However, in spite of its simplicity, it cannot be considered as a practical solution, because the accuracy, robustness and security of this technique are questionable. So it is a real challenge to achieve several design objectives at once. In fact, most of the existing techniques fulfil only a few design objectives, while compromising others. For example, a complex technique is used in [42] to enhance the accuracy and robustness of the localisation system, but this affects the simplicity, security and energy efficiency of this system.

An efficient localisation algorithm was designed. This algorithm relies on using a low number of references to achieve an accurate estimation without compromising other design objectives (such as simplicity, self-organising properties, robustness, security and energy efficiency) of the algorithm. This algorithm was termed **a**n efficient **l**ocalisation algorithm for **w**ireless **ad** hoc sensor networks with **h**igh **a**ccuracy (ALWadHA). The ALWadHA algorithm is based on a smart reference-selection method, which has the following characteristics:

- Requires a very simple computation. This method selects references based on location error using the probability of accuracy of the available references. Estimating the probability of accuracy requires only one division and few addition operations and it does not require any collaboration between neighbour nodes.

- Selects a low number of references, almost equal to the minimum possible number of references, which is three references. This reduction in the number of references used greatly improves the simplicity, accuracy and energy efficiency of the localisation algorithm.

- Is not an elimination method, based on eliminating a few references, but a real selection method. (The main disadvantage of the elimination method is that it could end up using all the available references or delete only a few of them.) Unlike most of the other techniques based on eliminating some references that do not satisfy certain conditions, the proposed method initially uses the minimum number of references, which is three references, and then checks if the selected subset satisfies a certain condition. If not, it adds one more reference and rechecks.

- Is smart, in the sense that it specifies the number of required references dynamically during the run time, based on the accuracy levels of the available references. The nodes close to beacons with high accuracy may use only a subset of three references, while those that have neighbour references with low accuracy will slightly increase the number of references used to overcome the error.

- Is not based on a specific distance-measurement model and can be used with any technique (e.g. RSS, TOA, RTT) without any modifications.

- Selects the best subset of references that enables nodes to estimate their position with high accuracy without involving a high number of references.

Using this smart reference-selection method not only enhances the accuracy of position estimation but also improves robustness, energy efficiency and security. The ALWadHA algorithm meets the following design objectives:

- **Accuracy:** The main objective of the ALWadHA algorithm is to determine the nodes' position with high accuracy. To achieve this, the localisation algorithm should not introduce a high estimation error and should be able to deal with accumulative computation error. The ALWadHA algorithm uses several techniques to accomplish these requirements. ALWadHA uses a smart reference-selection method that selects the best subset of references. This method requires simple computations that do not cause a high error rate. Finite precision is one source of error that influences localisation performance in WSNs. This type of error is due to inaccuracies induced by the limited computation precision of digital computers. These errors are important in WSNs because the sensors are resource constrained [16]. Therefore, reducing the complexity of computation could reduce the errors originating from this source.

  In the successive-refinement approach, which is used by ALWadHA, M_Refine and NDBL algorithms, the nodes keep re-estimating their position to enhance the accuracy of estimation. However, this approach could be influenced by the accumulated error, which increases gradually after each iteration. ALWadHA reduces the impact of the cumulative computation error by using a termination criterion that halts the process of estimation as soon as the node estimates its position with good accuracy. Moreover, unlike other successive-refinement algorithms, ALWadHA does not use the current estimated position to estimate the refined position in the next iteration; instead, it helps to specify the references that will be used and to check if the new refined position will be accepted. Simulation results show that, in cases where measurements are error free, the mean error using the ALWadHA algorithm is close to zero (0.00078 % of r_{tx}). In comparisons with other localisation algorithms, the mean error of the M_Refine algorithm increased gradually (0.97 % of r_{tx}) because of the computation error that accumulated during the refinement phases. The NDBL algorithm has a high mean error rate (27.95 % of r_{tx}), caused by the algorithm itself and the cumulative error during the refinement phases.

The accuracy of the ALWadHA algorithm was investigated with regard to several factors, such as node deployment, node density, network size and distance-measurement error. In all of these scenarios, the ALWadHA algorithm has excellent accuracy compared with other localisation algorithms. Simulation results also show that using the ALWadHA algorithm allows nodes to determine their position with high accuracy after a low number of iterations. This reduction in the required number of iterations dramatically reduces the computation cost. Therefore, it also could reduce the impact of errors that come from a finite precision source.

- **Self-organising properties:** Localisation algorithms should be independent of global infrastructure and beacon placement. Several localisation algorithms require particular beacon placement or require the beacons to be placed in a specific pattern. For example, [30] requires a triangle placement of beacons in a certain location. Several works in the literature have investigated the proposed localisation algorithms using only a specific scenario, such as a grid deployment, a low number of nodes or a small network.

  The ALWadHA algorithm does not depend on any specific node deployment and does not require a particular beacon placement. To investigate this design objective, two types of deployment were simulated: random and grid deployment. In random deployment the nodes are distributed randomly on the network, while in a grid deployment the beacons are placed inside grid cells selected randomly and the other nodes are then placed in the rest of the grid cells. In each experiment, the simulation was run 100 times and at each run the nodes were redistributed randomly. The ALWadHA algorithm was also investigated using different scenarios, varying the number of unknowns and beacons, and size of network. Simulation results showed that ALWadHA algorithm outperforms other localisation algorithms using these same scenarios in terms of estimation accuracy, energy efficiency and the number of references used.

- **Simplicity:** The ALWadHA algorithm took into account the limited resources of sensor nodes and it was designed to be as simple as possible without compromising other design objectives. The core of the ALWadHA algorithm is the smart reference-selection method. This method follows several techniques to achieve simplicity, such as selecting references using their probability of accuracy, estimating this probability using only one division and few addition operations; and selecting only a few references, which greatly reduces the computation cost.

  The ALWadHA algorithm deals with location error and distance-measurement error separately, using filter two and filter three respectively. Filter two is used to select a subset of references based on location error, while filter three is used to eliminate those references with high distance-measurement error (see Section 4.4 for a detailed discussion of these filters). The ALWadHA algorithm always uses filter two to estimate the initial position. Filter two is based on the probability of accuracy, which requires very simple computations. The ALWadHA algorithm uses filter three only when there is at least a reference in the subset used that has a high distance-measurement error. Dealing with the two types of error separately also reduces the computation cost.

  Simulation results show that the ALWadHA algorithm uses a low number of references, almost equal to the minimum possible number of references (which is three references). Moreover, it performs a lower number of iterations compared with other refinement-localisation algorithms, such as the NDBL and M_Refine algorithms. The simplicity of the ALWadHA algorithm could enhance not only the accuracy of estimation but also resource usage, such as CPU usage and memory space required.

- **Robustness:** Relying on using all or most of the available references to enhance the accuracy of estimation could reduce the robustness of the localisation algorithm. A high number of references might not be available in WSNs because sensor nodes are prone to failure from lack of power or physical damage, or they could be unreachable because of obstacles or node movements. The ALWadHA algorithm allows nodes to determine their positions using only a few references. This makes ALWadHA very tolerant of node failures.

The ALWadHA algorithm uses three types of filter to deal with localisation errors. The first filter is used by known nodes, while the other two filters are used by the node itself. Filter one is used to ensure that only the known nodes with high accuracy will send their "location response" packets. Filter two is used to deal with location error based on the probability of accuracy. Filter three is used to deal with distance-measurement error. In addition to these filters, the ALWadHA algorithm uses the successive-refinement approach, which also enhances the robustness of the ALWadHA algorithm. Simulation results proved the robustness of the ALWadHA algorithm and showed that even with underlying measurement error, ALWadHA achieves acceptable accuracy that is, on average, not much worse than the basic measurements. When an error was added with a standard deviation equal to 10% of the measured distance, the mean error of ALWadHA was only 18.39% of transmission range (r_{tx}); for M_Refine it was 21.62% of r_{tx} and for NDBL it was 41.58% of r_{tx}. The mean error of the single-estimation algorithms was much higher; for example the mean error for the Nearest algorithm was 77.54% of r_{tx}.

- **Energy efficiency:** In order to make ALWadHA an energy-aware localisation algorithm, several techniques are followed to reduce computation and communication overheads. To reduce the computation overheads, the ALWadHA algorithm uses simple computation, requires few references and uses a termination criterion to reduce the number of iterations. To reduce the communication overheads, the ALWadHA algorithm reduces the number of propagated messages required by the localisation system, i.e. the "location request" and "location response" packets. The ALWadHA algorithm uses a termination criterion to halt the process of localisation as soon as the node has determined its position with good accuracy. The use of this criterion reduces the number of "location request" packets. Filter one is used to reduce the number of "location response" packets by allowing only references with high accuracy to send their responses. Simulation results showed that the ALWadHA algorithm required a lower number of "location request" and "location response" packets and consumed less energy than other successive-refinement localisation algorithms.

- **Localised algorithm:** The localised algorithms used for location discovery should comply with the following three conditions: Firstly, they should request and process information with regard to the localisation algorithm only locally, without any central coordination overhead. Secondly, only a subset of nodes should take part in the position estimation process. Finally, the selected subset should be the one most likely to contribute to high, accurate position estimation. The ALWadHA algorithm completely satisfies these three conditions. Therefore, it can be regarded as a localised algorithm. It has moreover been shown that using a localised information-fusion technique based on an efficient reference-selection method would enhance the performance of the algorithms and attain several design objectives. Information fusion can play a leading role in localisation algorithms by guiding the location-discovery process simultaneously with the fusion process.

- **Information fusion:** The ALWadHA algorithm does not use information fusion in a supporting role that assists only in position estimation. Information fusion in the ALWadHA algorithm plays a leading role that guides the location-discovery process and the fusion process simultaneously. When the possibility of integrating information fusion with the localisation system was investigated; it was realised that the best way to achieve this goal would be to use a localised algorithm. Information fusion used in localisation algorithms was classified into three levels and the discussion showed how the ALWadHA algorithm used these three levels to allow nodes to determine their position with high accuracy and at the same time achieve several information-fusion objectives. Simulation results showed that using these three levels of information fusion greatly improves the accuracy, simplicity, robustness, security and energy efficiency of the ALWadHA algorithm.

- **Security:** Wireless sensor networks require a secure localisation system that is able to work in a hostile environment and to prevent compromised nodes from participating in the localisation process. A secure localisation system should consider the security aspects of the three components of this system, namely the distance/angle estimation, position computation and localisation algorithm. To provide secure distance estimation, the use of a distance-bounding approach was suggested for ALWadHA. Distance bounding is simple to integrate, does not require synchronised clocks, performs well in the WSNs environment, involves only two nodes to estimate the distance between them, and adds minimal overheads to ALWadHA. However, using a secure distance-bounding protocol is not enough to secure the entire localisation system. Therefore, the ALWadHA algorithm also uses a robust position-computation component that tolerates the existence of malicious nodes.

The filter three that is used in the ALWadHA algorithm not only enhances localisation accuracy, but could also enhance the security of the algorithm. Malicious nodes provide incorrect location information to mislead other nodes. However, pretending to be in a different location increases the difference between the measured and estimated distance, which makes it easy for filter three to detect it, and these malicious nodes will consequently not participate in the localisation process. Simulation results showed the attack-resistance of the ALWadHA algorithm and proved that ALWadHA is able to determine nodes' position in the hostile environment without undermining the estimation accuracy.

Therefore, it can be said that the hypothesis of this study, that a *localisation algorithm can rely on using a low number of references to achieve an accurate estimation without compromising the simplicity, security, robustness or the energy efficiency of the algorithm,* has been proved.

6.2 SUMMARY OF CONTRIBUTIONS

This section will summarise the main contributions of this work into three areas: smart selection localisation; information fusion in localisation systems; and distance-bounding protocols.

- **Smart selection localisation:**

  This thesis proposed a novel localisation algorithm (ALWadHA) to solve the problem of determining sensor nodes' location. ALWadHA is based on a smart reference-selection method. The main unique characteristics of this algorithm may be outlined as follows:

  - It relieves the burden of using a high number of references to achieve good accuracy. Relying on using a high number of references in WSNs could lead to several problems.

- It uses a novel smart reference-selection method that is not based on measured distance (which could be corrupted by multiplicative noise).
- It considers the three types of error (i.e. computation error, distance-measurement error and location error) and deals with them separately.
- It employs the three levels of information fusion to enhance the performance of the algorithm.
- It achieves good performance under various operational conditions, such as an error-free environment, noisy environment and hostile environment.
- Unlike other successive-refinement algorithms, it does not use the current estimated position to estimate the refined position in the next iteration; instead it uses it to help specify the references that will be used and to check whether the new refined position will be accepted.

Most of the localisation algorithms in the literature are based on using all the available references. In contrast, only limited research has been done on selecting a subset of references. Each of these previous algorithms targets only one or a few design objectives. However, none of them is able to achieve all the design objectives. The proposed algorithm accomplishes several design objectives, which can be considered an achievement that provides more motivation for this investigation.

- **Information fusion in localisation systems:**

  Research on analysing localisation systems from the information-fusion perspective is hardly reflected in the literature. This thesis has presented an overview of localisation systems that are based on information fusion, and has shown that using a localised algorithm makes information fusion play a leading role. The thesis also analysed a number of approaches used by localised information-fusion algorithms, highlighted some of their strengths and weaknesses, briefly compared them and showed how designers could decide which approach should be followed to implement their localised algorithms. An intensive literature review showed that no similar analysis has been published.

Information fusion used in localisation algorithms was classified into three levels. Most of the existing localisation algorithms, especially those using all of the available references, use only the first level of information fusion, and that in a supporting role. The localised algorithms usually use the first two levels of information fusion. A very limited number of localisation algorithms have used level three of information fusion. However, these algorithms required additional interaction between nodes to achieve this level. The ALWadHA algorithm employs the three levels of information fusion and does not require any interaction between nodes to achieve the third level.

- **Distance-bounding protocols:**

This thesis has discussed a range of techniques for distance estimation, with more focus on the distance-bounding technique. It conducted an analysis of aspects and performance with regard to using distance bounding in WSN localisation. Thereafter, the use of a distance-bounding approach was suggested as a promising solution for localisation systems, and especially for the proposed algorithm. The thesis gave an overview of distance bounding and provided a comparative study of selected distance-bounding protocols. The result illustrates the practical resource requirements and performance trade-offs involved in different protocols, and could act as a guide for choosing a suitable distance-bounding protocol when implementing a secure distance-estimation component for localisation systems in WSNs. Although a few works have given a limited comparison of distance-bounding protocols, they are not as comprehensive as the one in this thesis. Moreover, none of them discusses aspects of using distance bounding in WSN localisation.

6.3 FUTURE WORK

Determining the position of nodes in WSNs is an interesting and challenging research area with many unsolved problems. The work presented in this thesis answers a few questions, while it opens the door to many more new riddles. Future challenges and a possible continuation of this work can be summarised as follows:

- **Mobile sensor networks:** The ALWadHA algorithm was developed and investigated with static WSNs in mind. An extension of this algorithm could be done by modifying and investigating the applicability of the ALWadHA algorithm to mobile sensor networks.

- **Energy efficiency:** One of the most important challenges is enhancing the energy efficiency of the proposed algorithm. Despite the ALWadHA algorithm's consuming less energy than other successive-refinement localisation algorithms, future research is required to achieve more energy efficiency.

- **Distance-bounding protocol:** Several proposals are still vulnerable because of the way the communication channel is implemented. Currently, there are very few practical implementations of distance-bounding channels suitable for WSNs; and while the number of distance-bounding protocols continues to increase, practical channels suitable for distance bounding remain a relatively unexplored topic for the future. Tippenhauer and Čapkun [118] have demonstrated a distance-bounding channel using off-the-shelf UWB components, which takes into account the security uncertainty introduced at the packet format layer, but otherwise channels have mostly been defined for near-field RFID systems [134] or contact smart cards [135].

- **Secure localisation system:** Implementing a secure localisation system is another challenging area. This system requires the following: firstly, integrating distance bounding into a localisation scheme (such as ALWadHA or an extension of it). The distance-bounding protocol used should adhere to the 'principles of secure distance bounding' defined in [89] and suitable for WSNs. Secondly, the performance must be evaluated, both in terms of overheads and resistance to attack.

- **Implementation with real motes:** This thesis assessed the performance evaluation and the design objectives of the proposed algorithm analytically and by computer simulations. An extension of this work to actual implementation of the ALWadHA algorithm and field testing on wireless sensor nodes would be a challenging task. Moreover, testing the ALWadHA algorithm in real applications, which require location knowledge of equipment or people using WSNs in areas such as robust situational awareness in underground mining, would be an interesting topic for future research.