Energy Efficient and Secure Wireless Communications for Wireless Sensor Networks

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Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements.

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Abstract

This dissertation considers wireless sensor networks (WSNs) operating in severe environments where energy efficiency and security are important factors. This main aim of this research is to improve routing protocols in WSNs to ensure efficient energy usage and protect against attacks (especially energy draining attacks) targeting WSNs.

An enhancement of the existing AODV (Ad hoc On-Demand Distance Vector) routing protocol for energy efficiency, called AODV-Energy Harvesting Aware (AODV-EHA), is proposed and evaluated. It not only inherits the advantages of AODV which are well suited to ad hoc networks, but also makes use of the energy harvesting capability of sensor nodes in the network.

In addition to the investigation of energy efficiency, another routing protocol called Secure and Energy Aware Routing Protocol (ETARP) designed for energy efficiency and security of WSNs is presented. The key part of the ETARP is route selection based on utility theory, which is a novel approach to simultaneously factor energy efficiency and trustworthiness of routes in the routing protocol.

Finally, this dissertation proposes a routing protocol to protect against a specific type of resource depletion attack called Vampire attacks. The proposed resource-conserving protection against energy draining (RCPED) protocol is independent of cryptographic methods, which brings advantage of less energy cost and hardware requirement. RCPED collaborates with existing routing protocols, detects abnormal sign of Vampire attacks and determines the possible attackers. Then routes are discovered and selected on the basis of maximum priority, where the priority that reflects the energy efficiency and safety level of route is calculated by means of Analytic Hierarchy Process (AHP).

The proposed analytic model for the aforementioned routing solutions are verified by simulations. Simulations results validate the improvements of proposed routing approaches in terms of better energy efficiency and guarantee of security.

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List of Abbreviations

AHP	Analytic Hierarchy Process
AODV	Ad hoc On-demand Distance Vector
ASW	Anti-Submarine Warfare
CBR	Constant Bit Rate
DAG	Directed Acyclic Graph
DoS	Denial of Service
DSR	Dynamic Source Routing
FIFO	First-In First-Out
GPS	Global Positioning System
MCDA	Multi Criteria Decision Analysis
RREP	Route Reply
RREQ	Route Request
SDT	Soldier Detection and Tracking
WSN	Wireless Sensor Network

Chapter 1

Introduction

Ad hoc networks are defined as self-configuring networks without infrastructure that are made up of mobile devices [106], and wireless sensor networks (WSNs) are a subset of ad hoc networks in which the “devices” are wirelessly interconnected sensor nodes. Sensor nodes may have functions including sensing, data relaying and data exchanging with other networks outside the WSNs [118], the number of nodes within a WSN may vary from a few to hundreds of thousands. WSNs are initially motivated by military applications (e.g. enemy detection and nuclear, biological or chemical attack detection), and later expanded to a wide range of civil applications, for instance, environmental applications (e.g. animals tracking, forest fire detection, and chemical leakage detection) and commercial applications (e.g. vehicles tracking) [121].

The general purpose of deploying WSNs is to transmit the useful information from any node to the desired destination. Usually this cannot be completed by direct transmission, and the data packet may travel through one or more intermediate nodes before reaching the destination. Thus the routing process to determine the best path between nodes is an important issue in WSNs.

In general, routing protocols have been studied extensively and numerous routing protocols have been proposed [92, 106]. Routing can be affected by multiple factors, or restrictions, two of them are quite crucial for WSNs: energy (restricted battery life of sensors) and security concerns (potential attacks from intruder). In this dissertation, we are motivated to inquire into better routing solutions supporting WSN applications under the aforementioned constraints.

The reminder of this chapter is organized as follows. The motivations and research problems are presented in Section 1.1 and Section 1.2, respectively, followed by the background knowledge in Section 1.3. The contributions are addressed in Section 1.4. Section 1.5 presents the outline of this dissertation.

1.1 Motivations

While WSNs are useful for a wide variety of applications, this dissertation is focused on applications operating in extreme environments such as the battlefield and contaminated region, where the risk of harm prohibits any manual engineering work. Various WSN applications can be deployed in the battlefield. For soldier detection and tracking (SDT), unattended acoustic and seismic sensors are deployed at specific points to detect the approach of enemy soldiers in order to protect military sites or buildings [72]. At a distance, sensors can detect typical sounds made by soldier activities, e.g. walking, crawling, weapon handling, and talking. Another example of interest here is littoral anti-submarine warfare (ASW) that utilizes small and low cost sensors equipped with passive or active sonar, which can be deployed in large numbers (hundreds or thousands) to provide a high density sensor field to detect enemy submarines [107]. These sensors have a short detection range and are far less susceptible to multi-path reverberations and other acoustic artefacts.

For a reliable deployment of these aforementioned applications, some underlying issues need to be solved including energy efficiency, security guarantees and so on. Considering the inherent properties of the selected WSN applications, various aspects of the problems should be noted:

- First, nodes are usually deployed without careful pre-planning (e.g. airdrop deployment) since the nominated WSN applications operate in dangerous zones, and sending engineers to carry out precise deployment is not preferable. Thus network topology is not known a priori, and will likely change over time due to exterior forces (e.g. explosions and movements). The networks are ad hoc by necessity in these environments.

- Second, the nodes in the applications of interest are often physically unreachable after deployment. Consequently, replacement of the energy source (typically a battery) is difficult or impossible. In order for the network to operate as long as possible, nodes may be capable of harvesting energy, and network routing protocols should select routes to minimize energy cost.
- Third, the network faces the risk of attacks to interfere with operations, such as selective forwarding, wormhole attacks, sinkhole attacks, and Sybil attacks [49]. Nodes may become compromised which could be very difficult to detect. It is commonly assumed that compromised nodes may exhibit suspicious behaviour, which is monitored and factored into a reputation system that calculates a reputation for every node and adapts route selections to avoid nodes with low reputations. Moreover, suspected nodes are prevented from participating in the routing protocol.

Some research has been carried out on energy efficient routing, secure routing, or even hybrid energy efficient and secure routing [4, 28, 42]. In terms of energy efficiency, most earlier works just focused on optimizing the routing protocol without considering the adoption of an external energy source (e.g. energy harvesting); on the other hand, guarantee of security highly depends on encryption, which can be a heavy computation cost for sensor nodes that usually have limited computing capability and energy capacity. Therefore, we are motivated to design analytical models and simulation tools to investigate the energy and security performance of WSNs, and try to figure out some routing approaches that take advantage of energy harvesting technology independent of cryptographic authentication, without compromising energy efficiency and security.

1.2 Research Problems

All throughout this dissertation, the main intention is to improve the performance and reliability of WSNs. To this end, based on the discussions above, we shall focus the research work on the following topics: energy efficiency and security. The research problems related to the topics will be investigated based on the inherent properties of WSNs, and we aim to propose solutions while paying attention to the characteristics of nominated WSN applications working in severe environments.

The first goal is to explore the possible external energy source that can be applied in WSNs. The available energy that can be harvested from the external energy source (e.g. solar energy harvested from sunlight) shall be statistically modelled. Based on the discovered energy harvesting model, it is expected to propose an enhanced (energy harvesting aware) Ad hoc On-Demand Distance Vector (AODV) routing protocol to improve the energy efficiency of network. The proposed protocol shall exhibit better performance in terms of lower overall energy consumption in data transmission. It is also preferable that the proposed protocol is designed without adding too much complexity.

In addition to the energy efficiency, this dissertation also targets security issues in WSNs. With respect to securities, the second research problem is set in the dissertation is to discover a way to analyse nodes' behaviours, and extract useful information that can be further utilized in routing. The status of the sensor nodes shall be evaluated by watching and recording their behaviours, and the trustworthiness of nodes can be determined quantitatively. Based on the watching records, it is expected to propose a trustworthiness determination scheme that issues a novel way to detect compromised nodes in the network.

This dissertation also aims to find a valid way to combine the energy efficiency and security concern in routing for WSNs. While previous routing protocols have been proposed for energy efficiency or security separately, a novel method that fuses the two concerns shall be figured out. In the end, it is expected to propose a new routing protocol that here balances the two concerns (energy efficiency and security) simultaneously by means of the aforementioned novel method.

The final goal is to study a specific type of attack (Vampire attack) targeting the energy storage of WSNs. Existing routing solutions against Vampire attack are heavily relied on cryptographic authentication, while this dissertation is trying to propose a routing solution independent of the power consuming cryptographic methods. Certain information of previous transmissions in the network are recorded, and an energy efficient malicious node detection method shall be presented with the help of those transmission records. Based on the results, it is expected to provide a routing protocol that can bypass potential compromised nodes as much as possible in route discovery while paying attention to energy efficiency.

1.3 Background Knowledge

1.3.1 Overview of the Energy Harvesting Technology

As mentioned in Section 1.1, one interesting feature of the nominated WSN applications in this dissertation is that the nodes are often unreachable after deployment, as a result replacement of energy source (usually battery) is difficult or even impossible. In this case, when the energy of a node goes down the only option is deploy a new one and bring extra cost, hence we intend to make the nodes work as longer time as possible and energy efficiency become crucial under the provision of limited energy storage. To tackle this issue, some efforts on improving the energy efficiency of routing protocol itself have been made, such as the routing method described in [90] develop a way to minimize energy consumed for routing data packets, but the shortage is that location information is required.

Another solution is to introduce external energy source, thus the concept of renewable energy can be taken into account, and this kind of energy can be harvested from the surrounding environment in various forms [98]. A typical energy harvesting system consists of three components: energy source, harvesting architecture and the

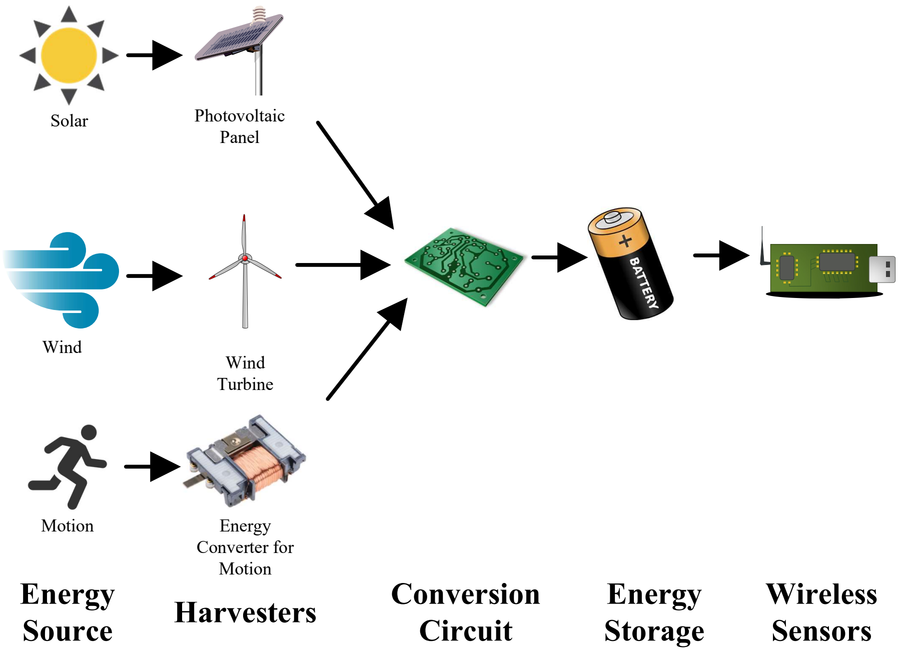


Fig. 1.1 Energy harvesting sources: solar wind, and motion

load, where energy source is the source of energy that could be collected from (e.g. solar, wind, and thermal), harvesting architecture implies the mechanisms that how the energy is harvested and transformed to electricity, and load represents the consumption of harvested energy [104].

There are various sources from which energy can be collected (Figure 1.1 shows some common examples): the sunlight, or so called solar energy (solar cell is a common application) is the easiest way to get energy from and can supply a power of approximately $15mW/cm^2$ [13, 91]. Basically, solar energy is not controllable and varies over time, but since the length of daylight on any specific date could be estimated accurately (even some cell phone application could do this job well), its statistical property could be analysed; another choice for free energy source is wind (anemometer is an example application), as same as solar, it is uncontrollable but can be statistically modelled [47], and could generate as much as 1200 mWh of energy each day [77]; there are some other alternative energy sources which are related to the motion (practical examples include piezoelectric material, Ratchet-flywheel, micro-generator and so on) of human-being such as footfalls, breathing and blood pressure [103].

Among aforementioned potential candidates, wind power is not suitable for WSNs as the size of wind driven generator is too bulky to be mounted on a wireless sensor node. Motion power is also off the table since the WSN applications we are talking about are deployed in severe environment in which human activities are rare (means very limited energy source or even does not exist). The solar power is quite considerable because not only the sunlight is easy to access, but also the solar panel could be made small enough to be mounted on the wireless sensor nodes.

Then sensors with energy harvesting device can be deployed in the network and may contribute to reduction of the transmission cost. On the other hand, since the factor “energy harvesting” is injected, the existing mechanism of the WSNs might be affected, such as routing strategy, which brings opportunities of improving the existing routing solutions by taking advantage of the energy harvesting technology.

1.3.2 Security Issues in WSNs

Talking about the military WSN applications mentioned in Section 1.1, they are naturally under the threats from enemies, who are keen on paralysing the functionality of those WSNs. In general sense, security threats on WSNs have been well studied [123], most of these previously studied various types of attacks have a common feature: they interfere the functionality of network immediately, or in short term. Thus even the source of these attacks may not be determined promptly, but the disruptions caused are enough to trigger an alarm indicating that attacks are under way, and afterwards the network operator would take actions to mitigate or eliminate (if possible) the effect of these attacks sooner or later. From the attackers’ perspective, this kind of attack pattern may have very limited availability, especially when their targets are for military use, which means the users of WSNs have taken potential security threats into consideration before deployment.

Take the enemy down stealthily is kind of a basic military strategy, the attackers who are always targeting our networks may do the same trick. Instead of disrupting the immediate (or short-term) availability of the network, there is a special type of attacks may seek to undermine the network over time, disrupt its long-term availability without being noticed. They are so called Vampire attacks [110] that try to deplete the network resources (e.g. energy storage on nodes, usually batteries) silently. Since the WSN applications (such as environmental surveillance and enemy detection) we focused on are operating in extreme environments, they are very sensitive to energy storage and the damage of Vampire attacks can be fatal.

1.4 Dissertation Contributions

Research in this dissertation is intended to directly benefit WSN applications working in severe environments. This dissertation is expected to provide energy efficient, reliable and secure routing solutions for the relevant WSN applications. The main contributions are the following.

First, this dissertation considers energy efficiency of routing protocols in WSNs. Many routing protocols for sensor network have been proposed, some of them tried to cope with the ad hoc nature while some others focused on improving the energy efficiency. We propose an Energy Harvesting Aware Ad hoc On-Demand Distance Vector Routing Protocol (AODV-EHA) that not only inherits the advantage of existing AODV in dealing with WSN's ad hoc nature, but also makes use of the energy harvesting capability of the sensor nodes in the network, which is very meaningful to the data transmission in the environmental and military applications under consideration. Simulation results show the proposed routing protocol has an advantage over competing routing protocols in terms of energy cost for data packet delivery.

Second, this dissertation presents a new routing protocol called Secure and Energy Aware Routing Protocol (ETARP) designed to improve energy efficiency and security for WSNs. The key part of the routing protocol is route selection based on utility theory. The concept of utility is a novel approach to simultaneously factor energy efficiency and trustworthiness (a Bayesian network is used to estimate the trustworthiness of nodes which is a different approach from previous literature) of routes in the routing protocol. ETARP discovers and selects routes on the basis of maximum utility with incurring additional cost in overhead compared to the common AODV routing protocol. Simulation results show that in comparison to previously proposed routing protocols, namely AODV-EHA and LTB-AODV (Light-Weight Trust-Based Routing Protocol), the proposed ETARP can keep the same security level while achieving more energy efficiency for data packet delivery.

At last, we look into an instance of resource depletion attack – Vampire attacks, and provide a resource-conserving protection against energy draining (RCPED) protocol which is independent of cryptographic methods. RCPED collaborates with existing routing protocol, detects abnormal signs of Vampire attacks and determines the possible attackers. Route selection in RCPED is based on Analytic Hierarchy Process (AHP). The concept of AHP is an approach developed to help making decisions (in our case, choosing the best route) under multiple concerns (in our case, energy efficiency and risk level of routes under Vampire attacks). RCPED discovers and selects routes on the basis of maximum priorities which a calculated by AHP. Simulations results show that RCPED achieves the minimum overall energy cost (overall energy cost reflects the energy efficiency performance and security performance simultaneously), in comparison to existing routing protocols, i.e. AODV-EHA and PLGPa.

1.5 Dissertation Outline

The rest of the dissertation is organized as follows. The related work about WSN relevant topics are introduced in Chapter 2. Starting from the routing issues of WSNs, it gives an overview of existing routing solutions with various concerns, from which WSN applications could benefit from. Next, we give a brief review of security threats that may interfere with the functionality of WSNs, followed by the countermeasures already proposed.

Chapter 3 introduces the AODV-EHA routing protocol for nominated WSN applications. The feasibility of adopting energy harvesting technology in routing protocol for WSNs is discussed, afterwards we summarize background knowledge and theoretical analysis of the energy harvesting aware AODV-EHA and its competitors. Through simulations, the performances of AODV-EHA are evaluated and compared with the existing work.

Chapter 4 introduces the ETARP routing protocol for WSN applications operating in extreme environments. The central concepts (such as the use of utility theory) in the ETARP are presented. The methods to estimate energy consumption and risk of node compromise are explained. Energy efficiency performance and safety performance evaluations in terms of simulation results are presented and compared with existing routing solutions.

Chapter 5 investigates how to protect routing protocols from the Vampire attacks in a more energy efficient way. The details of detection over Vampire attacks are given. We also discuss how to mitigate the harm come with the attacks. Performance evaluations of the proposed solution in terms of overall energy cost, which reflect the energy efficiency performance and security performance simultaneously, are presented as well.

In the last chapter we summarize the whole dissertation and make some further discussions on future work.

Chapter 2

Literature Review

2.1 Routing Issues in WSNs

The main purpose of deploying WSNs is to transmit the useful information collected from sensor nodes to the desired destinations, and usually there are multiple choices of paths available. Determination of the best one, namely, the routing process is an important issue in WSNs. There have been tremendous works for the development of routing protocols in WSNs [3, 92, 106], furthermore, a lot of research is still ongoing. All these protocols can be classified into different categories, according to (including but not be limited to) application needs, architecture of the network, or protocol operation. For the sake of avoiding confusion, we use two categorizations, depending on network architecture and protocol operation, respectively, as illustrated in Figure 2.1.

2.1.1 Protocols Classification Based on Network Structure

Depending on the underlying network structure, routing protocols can be categorized into: flat, hierarchical, and location-based routing.

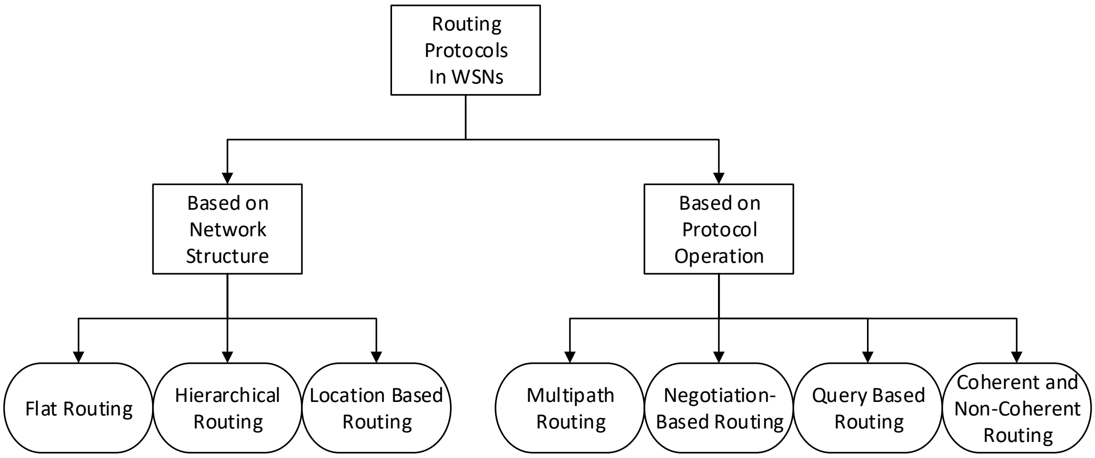

Routing Protocols In WSNs
Based on Network Structure
Based on Protocol Operation
Flat Routing
Hierarchical Routing
Location Based Routing
Multipath Routing
Negotiation-Based Routing
Query Based Routing
Coherent and Non-Coherent Routing

Fig. 2.1 Classification of Routing Protocols

Flat Routing

The term “flat” here implies that every node acts the same role in flat networks, and a flat addressing scheme is chosen in flat routing protocols [36]. In the rest of this subsection, we present some representative examples and highlight their characteristics.

Directed Diffusion [40] is data-centric, in that all communication is for named data. The sink node sends queries to certain regions and waits for data from the sensors located in the selected regions. In Directed Diffusion-based networks all nodes are application aware, which enables diffusion to achieve energy savings by selecting empirically good paths and by caching and processing data in-network. The evaluation and the performance results in [40] also show that even with relatively unoptimized path selection, Directed Diffusion outperforms an idealized traditional data dissemination scheme like omniscient multicast.

Sensor Protocols for Information via Negotiation (SPIN) [35] is a family of adaptive protocols. They efficiently disseminate information among sensors in an energy-constrained WSN. Nodes adopting a SPIN communication protocol use meta-data (data using high-level data descriptors) negotiations to eliminate the transmission of redundant data throughout the network. Furthermore, SPIN nodes can base their communication decisions both upon application-specific knowledge of the data and upon knowledge of the available resources. This enables the sensors to distribute data efficiently with a limited energy supply. The problem with SPIN is that it does not provide guarantee for data delivery, for instance, when an interested node is very far from the advertised, then that interested node will not get any data if nodes between these two nodes are not interested in the data.

Dynamic Source Routing (DSR) [45] adapts quickly to routing changes when hosts move frequently, yet only requires little or even no overhead during periods in which hosts move less frequently. This protocol performs well over a variety of environmental conditions such as host density and movement rates, according to the packet-level simulation results presented in this paper. However, in large networks where longer paths prevail, source routing packets cause larger overhead due to the stored path information.

In AODV [82], each mobile host operates as a specialized router, and routes are obtained as needed (on-demand) with little or even no reliance on periodic advertisements. AODV is quite suitable for a dynamic self-starting network, as required by users wishing to utilize ad hoc networks. AODV provides loop-free routes even while repairing broken links. In addition, this protocol requires no global periodic routing advertisements, the demand on the overall bandwidth available to the mobile nodes is significantly less than in those protocols that do necessitate such advertisements. On the other hand, AODV still inherit most of the advantages of basic distance-vector routing mechanisms. Nevertheless, since flooding is used for controlling message dissemination and route maintenance, routing control overhead may grow high [83].

The Topology Dissemination Based on Reverse-Path Forwarding Protocol (TBRPF) [7] uses the concept of reverse-path forwarding (RPF) to broadcast link-state updates in the reverse direction along the spanning tree formed by the minimum-hop paths from all nodes to the source of the update. Within TBRPF, the minimum-hop paths that form the broadcast trees are computed with the help of topology information received along this tree. The utilization of minimum-hop trees rather than shortest-path trees (based on link costs) results in less frequent changes to the broadcast trees (and less communication cost for maintaining the trees). However, TBRPF requires nodes to maintain routing tables containing entries for all the nodes in the network, this can bring negative effect to the scalability of the protocol, especially when user population is large (means large overhead).

Hierarchical Routing

Hierarchical, or the so called cluster-based routing methods, are with special advantages in scalability and efficient communication. The term "hierarchical" here means, higher-energy nodes with higher residual energy are used to process and send the information, while the ones with lower residual energy can be used to perform the sensing tasks. The formation of clusters and assigning special tasks to cluster heads can greatly improve the overall system scalability, lifetime, and energy efficiency. In the rest of this subsection, we present some representative examples and highlight their characteristics.

Low Energy Adaptive Clustering Hierarchy (LEACH) [34] is a clustering-based protocol that utilizes randomized rotation of local cluster base stations (cluster-heads) to evenly distribute the energy load among the sensors in the network. LEACH uses localized coordination to enable scalability and robustness for dynamic networks, and incorporates data fusion into the routing protocol to reduce the amount of information that must be transmitted to the base station. LEACH minimizes global energy usage by distributing the load to all the nodes at different timing. At different times, each node has the burden of acquiring data from the nodes in the cluster, fusing the data to obtain an aggregate signal, and transmitting it to the base station. LEACH is completely distributed, not requiring any control information from the base station, and the nodes do not need knowledge of the global network in order to maintain the operation of LEACH. However, LEACH uses single-hop routing where each node can transmit data to the cluster-head and the sink directly, hence, it may not be suitable for networks deployed in large regions.

Power-Efficient Gathering in Sensor Information Systems (PEGASIS) [61] is a near optimal chain-based protocol that is an enhancement over LEACH. In PEGASIS, each node communicates only with a nearby neighbour and takes turns transmitting to the base station, in order to reduce the amount of energy spent per round. PEGASIS outperforms LEACH by eliminating the overhead of dynamic cluster formation, minimizing the distance non leader-nodes must transmit, limiting the number of transmissions and receives among all nodes, and using only one transmission to the base station per round. The drawback of PEGASIS protocol is the redundant transmission of the data. This is due to the fact that PEGASIS does not consider the base station's location about the energy of nodes when one of them is selected as the head node.

Hierarchical State Routing (HSR) [79] is a soft state wireless hierarchical routing protocol. The authors distinguish between the "physical" routing hierarchy (dictated by geographical relationships between nodes) and "logical" hierarchy of subnets in which the nodes move as a group HSR keeps track of logical subnet movements using Home Agent concepts similar to Mobile IP. Compared with flat, table driven routing schemes (such as DSDV (Highly Dynamic Destination-Sequenced Distance-Vector Routing) [81]) HSR achieves a much better scalability, at the cost of non-optimal routing and increased complexity.

Cluster Head Gateway Switch Routing (CGSR) [21] is a multicast protocol inspired by the Core Based Tree approach (initially developed for the internet). CGSR is robust to mobility, has low bandwidth overhead and latency, scales well with membership group size, and can be generalized to other wireless infrastructure (other than hierarchical). Nevertheless, it is difficult for CGSR to maintain the cluster structure in a mobile environment.

Location Based Routing

In this type of routing, sensor nodes are addressed according to their locations. The location of nodes may be obtained from a satellite if nodes are equipped with GPS (global positioning system) receiver [116]. Alternatively, nodes can estimate the distance from neighbours based on incoming signal strengths. Afterwards, the relative coordinates of neighbouring nodes can be determined by exchanging distance information between neighbours [9, 10, 97]. In the rest of this subsection, we present some representative examples and highlight their characteristics.

Geographic Adaptive Fidelity (GAF) [116] saves energy by identifying nodes that are equivalent from a routing perspective and then shutting down unnecessary nodes, keeping a constant level of routing fidelity. GAF moderates this policy by using application-level and system-level information; nodes that source or sink data remain on and intermediate nodes monitor and balance energy use. GAF focus on turning the radio off as much as possible. It adapts sleep time based on node location scaling back node duty cycles (and so reducing routing "fidelity" when many interchangeable nodes are present. The authors have shown that it performs at least as well as a normal ad hoc routing protocol for packet loss and route latency while conserving substantial energy, and allowing network lifetime to increase in proportion to node density. But the requirement of GPS devices may be difficult for some networks.

SPAN [18] is a location-based and distributed coordination technique that reduces energy consumption without significantly diminishing the capacity or connectivity of the network. Within SPAN, nodes make local decisions on whether to sleep, or to join a forwarding backbone as a coordinator. Each node bases its decision on an estimate of how many of its neighbours will benefit from it being awake, and the amount of energy available to it. SPAN provides a randomized algorithm where coordinators rotate with time, demonstrating how localized node decisions lead to a connected, capacity-preserving global topology. But on the negative side, existing and new coordinators do not have to be neighbours, which in fact makes SPAN less energy-efficient because of the need to maintain the positions of two- or three-hop neighbours.

The Location-Aided Routing (LAR) [54] is an approach to utilize location information (for instance, obtained using the global positioning system) to improve performance of routing protocols for ad hoc networks. By using location information, the LAR protocols limit the search for a new route to a smaller "request zone" of the ad hoc network. This leads to in a significant reduction in the number of routing messages. Some algorithms are proposed to determine the so called "request zone", based on the expected location of the destination node at the time when route discovery is ongoing. Note that

LAR involves network-wise flooding to obtain location information, which makes the control overhead increases as the network grows.

2.1.2 Protocols Classification Based on Protocol Operation

Multipath Routing Protocols

In this type of routing, the protocol uses multiple paths instead of a single path, which has the advantage to enhance network performance. Furthermore, network reliability can be increased since multipath routing is more resilient to route failures (at the cost of overhead in maintaining alternative paths).

Label-based Multipath Routing (LMR) [37] is a routing protocol using only localized information. LMR can efficiently find a disjoint or segmented backup path to provide protection to the working path. LMR utilizes the label information to search segmented backup path if a disjoint path is not found, reducing overhead and delay. Furthermore, LMR can take advantage of local multicast, significantly reducing the routing overhead. However, to find the possible backup paths, LMR consumes extra overhead, to send label messages, label reinforce messages and backup exploratory messages.

In [16], the authors formulate the routing problem as to maximize the network lifetime. This problem formulation has revealed that the minimum total energy (MTE) routing is not suitable for network-wise optimum utilization of transmission energy. A shortest cost path routing algorithm is proposed which uses link costs that reflect both the communication energy consumption rates and the residual energy levels at the two end nodes. The algorithm is amenable to distributed implementation. It shows that significant improvement can be made in terms of maximizing the system lifetime, which can also be interpreted as maximizing the amount of information transfer between the source and destination nodes with limited energy supply.

The authors of [112] propose a Hierarchy-Based Multipath Routing Protocol (HMRP) for WSNs. In HMRP, the network will be constructed to layered-network at first. Based on the layered-network, sensor nodes will have multipath route to sink node through some candidate parent nodes. Because distributing the load to the nodes has a great impact on system lifetime, therefore main idea of HMRP is minimizing the path loading of the system by distributing the energy consumption among the nodes. In HMRP, sensor nodes do not to maintain the information of the whole path and they just keep their node information tables. The drawback of HMRP is that it broadcasts the layer construction packet only once.

Query Based Routing

In Query-based routing protocols, the destination nodes propagate a query for data, or so called sensing task, through the network, and a node with this data sends the data that matches the query back to the node that initiated the query [94]. Normally, these queries are described in natural language or high-level query languages.

The Directed Diffusion [40] which has been introduced earlier can be considered as an example of query based routing as well. In Directed Diffusion, the sink node sends its interest messages to sensors. As the interest messages are propagated throughout the network, the gradients from the source back to the sink are set up. When the source has data for the interest, the source sends the data along the interest's gradient path. For the sake of lower energy consumption, data aggregation is carried out en route.

Rumour routing [8] allows for queries to be delivered to events in the network. In rumour routing, each node maintains a list of its neighbours, as well as an events table, with forwarding information to all the events it knows. When a node witnesses an event, it adds it to its event table. Node also generates an agent probabilistically, where an agent is a long-lived packet, which travels the network, propagating information about local events to distant nodes. Any node can generate a query, which should be routed to a particular event. If the node has a route to the event, it will transmit the query. If it does not, it will forward the query in a random direction. If the node that originated the query determines that the query did not reach a destination, it can try retransmitting, give up, or flood the query. Rumour routing is tunable, and allows for trade-offs between setup overhead and delivery reliability, but the problem is that it may broadcast duplicated messages to the same node.

Negotiation-Based Routing

In this type of protocols, meta-data negotiations (high-level data descriptors through negotiation) are utilized to reduce redundant data transmissions. Communication decisions can be made based on the resources available to them as well.

The SPIN family protocols [35] mentioned earlier and the protocols in [56] are examples of negotiation-based routing protocols. The SPIN family of protocols consists of two basic ideas : first, sensor applications need to communicate with each other about the data that they already have and the data they still intend to obtain, so as to operate efficiently and to conserve energy; second, nodes must monitor and adapt to changes in their own energy resources to maximize the operating lifetime of the network.

QoS-based Routing

In QoS-based routing protocols, the network has to balance between energy consumption and data quality [1, 99]. Specifically, the network has to satisfy certain QoS metrics, such as delay, energy, bandwidth, and the like, when delivering data to the sink.

In the best-effort routing the main concerns are the throughput and average response time. QoS routing is usually performed through resource reservation in a connection-oriented communication that meet the QoS requirements for each individual connection. While many mechanisms have been proposed for routing QoS constrained real-time multimedia data in wire based networks, they cannot be directly applied to WSNs due to the limited resources, such as bandwidth and energy that a sensor node has.

Sequential Assignment Routing (SAR) in [100] is one of the first routing protocols for WSNs that introduces the concept of QoS in the routing decisions. Routing decision in SAR depends on the following factors: energy resources, QoS on each path, and the priority level of each packet. In order to avoid single route failure, a multi-path approach is used and localized path restoration schemes are adopted. The objective of

SAR algorithm is to minimize the average weighted QoS metric throughout the lifetime of the network. However, in order to maintain tables and states that store the above mentioned information at each sensor node, the overhead may be high, especially when the nodes number is large.

Another QoS routing protocol for WSNs that provides soft real-time end-to-end guarantees is SPEED [32], which is designed to avoid congestion when the network is congested. The routing module in SPEED is called Stateless Geographic Non-Deterministic forwarding (SNFG) and works with four other modules at the network layer. Compared to DSR and AODV which are mentioned earlier, SPEED performs better in terms of end-to-end delay and miss ratio. Furthermore, the total transmission energy and control packet overhead are less because of the simplicity of the routing algorithm. Nevertheless, the performance of of SPEED is not very good when the network is heavily congested.

Coherent and Non-coherent Based Routing

In operation of WSNs, data processing is a major component. The sensor nodes cooperate with each other in processing the data within the network. The routing mechanism which initiates the data processing module is proposed in [100]. This mechanism is divided into two categories: coherent and non-coherent data-processing based routing. For non-coherent based routing [46], the raw data is processed by sensor nodes locally before it is sent to other nodes (aggregators) for further processing. In coherent based routing, only minimum processing (such as time stamping and duplicate suppression) is done for raw data before it is sent to aggregators.

In [11, 100], Single Winner Algorithm (SWE) and Multiple Winner Algorithm (MWE) are proposed for non-coherent and coherent processing, respectively.

In SWE, a single aggregator node is elected for complex processing. This node is selected based on the energy reserves and computational capability of that node. At the end of the SWE process, a minimum-hop spanning tree will completely cover the network.

MWE is a simple extension of SWE. When all nodes are sources and send their data to the central aggregator node, a large amount of energy will be consumed. In order to lower the energy cost, limit the number of sources that can send data to the central aggregator node is a possible solution. Instead of keeping a record of only the best candidate node, each node will keep a record of up to n nodes of those candidates. At the end of the MWE process, each sensor in the network holds a set of minimum-energy paths to each source node. After that, SWE is utilized to determine the node that yields the minimum energy consumption.

2.2 Energy Efficient Routing Protocols

The most straightforward thinking of improving energy efficiency of WSNs is to design energy efficient sensors. Work was started in academic institutions, but a number of enterprises have joined the team in recent years, including companies such as Crossbow, Dust Networks, Ember Corporation, Sensoria and Wordsens. These commercial efforts make the sensor devices ready for real deployment in various WSN applications, together with a serious of tools for sensor programming and maintenance [76].

In parallel to the progress in sensor hardware, some efforts have been made to improve the energy efficiency of the routing protocols themselves. For example, the distributed position-based routing method described in [90] attempts to minimize the energy consumed for routing data packets, but the drawback is that location information is required. Given any number of randomly deployed nodes over an area, a simple local optimization scheme executed at each node guarantees strong connectivity of the entire network and attains the global minimum energy solution for stationary networks. Due to its localized nature, this protocol is self-reconfiguring.

Another approach of minimum cost message delivery studied in [119] is called Scalable Solution to Minimum-Cost Forwarding (SSMCF). This approach seeks the minimum cost path from any given source to a specific sink in sensor networks. This approach may not be suitable for some WSN applications because the sink (or destination node) is assumed to be fixed.

Efficient Minimum-Cost Bandwidth-Constrained Routing (EMCBCR) [15] is designed to select the routes and the corresponding power levels for the sake of maximizing the time until batteries of the nodes drain-out. EMCBCR is local and amenable to distributed implementation. If there is a single power level, the problem is reduced to a maximum flow problem with node capacities and the algorithms converge to the optimal solution. If there are multiple power levels then the achievable lifetime is close to the optimal most of the time. EMCBCR is a simple, scalable and efficient solution for minimum cost routing in WSNs. In fact the term “minimum cost” refers to maximum network lifetime, achieved by choosing the route with maximum energy reserve which is not exactly the same as a route with minimum energy cost.

2.3 Energy Harvesting Aware Routing Protocols

Another research direction to improve energy efficiency is to consider renewable energy from an external energy source. Renewable energy can be harvested from the surrounding environment by various means such as solar, wind, thermal, or motion [13], that is, energy harvesting which has been introduced in Section 1.3.1. Solar power is well suited to WSNs because not only sunlight is easy to access but also solar panels can be made small enough to be mounted on wireless sensor nodes.

A notable routing algorithm that is energy harvesting aware is the Distributed Energy Harvesting Aware Routing Algorithm (DEHAR) [42], which defines a new metric of “energy distance” (including energy harvesting) for selecting the best route. By this metric, DEHAR aims to find the route with minimum total energy distance rather than spatial distance. DEHAR calculates the shortest energy distance by using a method such as Directed Diffusion, a flooding mechanism incurring extra routing overhead.

Opportunistic Routing algorithm with Adaptive Harvesting-aware Duty Cycling (OR-AHaD) proposed in [6] is designed with energy management capabilities that consider variations in the availability of the environmental energy. OR-AHaD can

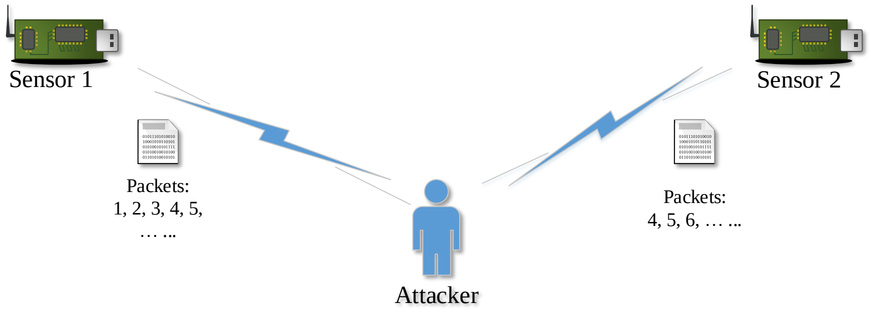


Fig. 2.2 Selective forwarding attack

adjust the duty cycle of each node adaptively in order to exploit the available energy resources efficiently in comparison to other opportunistic routing protocols. However, geographical information is required, which may not be well suited to some applications.

2.4 Conventional Types of Attack on WSNs

Security challenges in WSNs are similar to those in mobile ad hoc networks identified in [101, 123]. As being military applications, the network faces the risk of attacks from enemies to interfere with operations, such as selective forwarding, wormhole attacks, sinkhole attacks, and Sybil attacks [2, 49]. Nodes may become compromised which could be very difficult to detect. It is commonly assumed that compromised nodes may exhibit suspicious behaviour, which can be monitored and factored into a reputation system that calculates a reputation for every node and adapts route selections to avoid nodes with low reputations. Moreover, suspected nodes are prevented from participating in the routing protocol.

Below are examples of some conventional attacks that are the main threats to routing in WSNs.

2.4.1 Selective Forwarding Attack (Grey Hole Attack)

As illustrated in Figure 2.2, compromised nodes may refuse to forward certain messages and just simply drop them, so that they can never reach the original destination. This

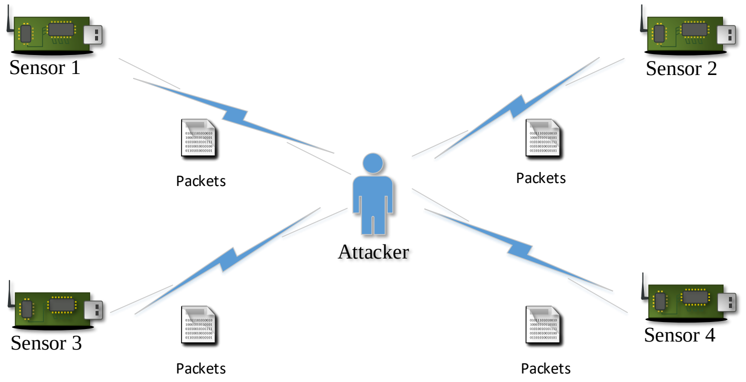


Fig. 2.3 Sinkhole attack

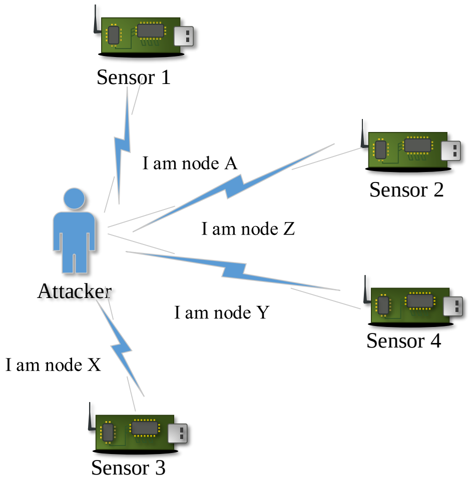


Fig. 2.4 Sybil attack

threat can make things even worse if a malicious node is explicitly included on the route [117].

2.4.2 Sinkhole Attack

As shown in Figure 2.3, a compromised node tries to attract all surrounding nodes to establish routes through itself. If the sinkhole attack is successful, then the network is also vulnerable to other attacks, such as eavesdropping or selective forwarding [71].

2.4.3 Sybil Attack

As illustrated in Figure 2.4 [117], the malicious node creates multiple fake identities to other neighbouring nodes in the network [70]. This Sybil attack is especially harmful to geographic and multipath routing protocols, since the malicious node can appear in multiple positions [49].

In addition, the authors of [69, 70] have discussed more routing attacks that can threat WSNs, e.g. fairness attack, sleep attack [85], and wormhole attack [51].

2.4.4 Existing Attack Countermeasures: Detection and Elimination of Malicious Behaviours

To deal with Grey hole attack, the Forwarding Assessment Based Detection (FADE) [63] scheme is proposed to mitigate collaborative grey hole attacks. Specifically, FADE detects sophisticated attacks by means of forwarding assessments aided by two-hop acknowledgement monitoring. Moreover, FADE can coexist with contemporary link security techniques. The optimal detection threshold, that minimizes the sum of false positive rate and false negative rate of FADE, is analysed while considering the network dynamics due to degraded channel quality or medium access collisions.

For sink hole attack, [73] present an algorithm for detecting the intruder. This algorithm first makes a list of suspected nodes, and then effectively identifies the intruder in the list through a network flow graph. The algorithm is also robust to deal with cooperative malicious nodes that attempt to hide the real intruder.

As to Sybil Attack, [122] investigates Sybil attacks and defence schemes in Internet of Things (IoT). The authors first define three types of Sybil attacks according to the Sybil attacker's capabilities, then present some Sybil defence schemes, including Social Graph-Based Sybil Detection (SGSD), Behaviour Classification-Based Sybil Detection (BCSD), and mobile Sybil detection with the comprehensive comparisons.

In [86] the authors develop a system-theoretic approach to security that provides a complete protocol suite with provable guarantees. This approach is based on a model capturing the essential features of an ad hoc wireless network that has been infiltrated with hostile nodes. The protocol suite caters to the complete life cycle, all the way from the birth of nodes, through all phases of ad hoc network formation, leading to an optimized network carrying data reliably. This approach has a distinguished feature: it supersedes much of the previous work that deals with several types of attacks (usually one approach can only deal with a specific type of attack) including wormhole, rushing, partial deafness, routing loops, routing black holes, routing grey holes, and network partition attacks.

2.4.5 Existing Attack Countermeasures: Efforts Made on Routing Solutions

Some existing routing protocols such as TinySec [48], SPINs [84], TinyPK [113], and TinyECC [62] attempt to eliminate unauthorized behaviour of malicious sensor nodes with the help of encryption or authentication on data packets. However, these solutions may be difficult for WSNs. For instance, data encryption is applicable for mobile ad hoc networks but generally not practical for WSNs because sensors have limited data processing capability and energy storage. Therefore, in addition to cryptographic solutions, routing algorithms that employ notions of trust and reputation have been proposed.

A trust-based reactive multipath routing protocol, Ad hoc On-Demand Trusted-path Distance Vector (AOTDV) [59], is an extension of the AODV routing protocol and the Ad hoc On-demand Multipath Distance Vector (AOMDV) [67] routing protocol. This protocol is able to discover multiple loop-free paths as candidates in one route discovery. These paths are evaluated by two aspects: hop counts and trust values. This two-dimensional evaluation provides a flexible and feasible approach to choose the shortest path from the candidates that meet the requirements of data packets for dependability or trust.

LTB-AODV [66], is light-weight in the sense that the intrusion detection system (IDS) used for estimating the trust that one node has for another, consumes limited computational resource. Moreover, it uses only local information thereby ensuring scalability. Our light-weight IDS takes care of two kinds of attacks, namely, the black hole attack and the grey hole attack. Whereas the proposed approach can be incorporated in any routing protocol. Note that the authors have used AODV as the base routing protocol.

The above two approaches passively observe forwarded data traffic and then calculate the risk level of different routes in terms of “trust values”, the routing algorithm then chooses the most trusted route. But there are some drawbacks: first, reputation system used in AOTDV or LTB-AODV watches for a single specific behaviour only; furthermore, they solely focus on security with no special attention given to energy efficiency concerns. Therefore, new routing solutions that can monitor multiple node behaviours and make comprehensive judgements on node status, while giving enough attention to the crucial energy efficiency are worth studying.

2.5 Routing Protocols Including Energy Efficiency and Security

There are a few papers starting to consider security and energy efficiency at the same time.

For instance, Ferng and Rachmarini [28] proposed a secure routing protocol for WSNs considering energy efficiency. With the location and energy-aware characteristics for routing, the protocol gives a better delivery rate, energy balancing, and routing efficiency. In addition, the proposed security mechanism ensures the data authenticity and confidentiality in the data delivery. But it has a disadvantage requiring information about node locations to improve energy efficiency. Furthermore, it depends on encryption which can be a heavy computation cost for sensor nodes.

Lightweight Secure LEACH (LS-LEACH) [4] aims to provide a secure and energy efficient routing protocol. Cryptographic authentication algorithm is integrated to assure data integrity, authenticity and availability. Furthermore, LS-LEACH shows its improvement over LEACH protocol that makes it secure and more energy efficient (by reducing the overhead from added security measures).

The above schemes generate extra overhead, thus the grantee of security with reduced energy cost could be a research of interest.

2.6 Security Concerns of Energy Depletion Attacks on WSNs

Since sensors deployed in WSNs have limited computation and energy resources, they are vulnerable to resource depletion attacks, such as Denial of Service (DoS) attack and the forced authentication attacks [33].

The power draining attack is a sub-category of resource depletion attack, given that battery is considered as the resource of interest. Rather than disabling the immediate availability, a power draining attack is trying to deplete the network's power over a long time horizon. Vampire attacks, an instance of the power draining attack, target routing protocols used in WSNs even those designed to be secure [110]. Vampire attacks are not protocol-specific. Instead, they exploit the general properties of routing protocols. Even worse, they use protocol-compliant messages, which makes themselves difficult to be detected and prevented.

Some simple attempts similar to Vampire attacks have been made, such as the power draining or resource exhaustion attacks described in [78, 102]. Rather than generating tremendous data to paralyse the network, Vampire attacks tend to inflict harm on the network little by little. Since Vampire attacks comply with the existing routing protocols, and data deliveries will be accomplished at the end (but just cost more resources than usual), these features make them even more difficult to be detected.

Existing routing protocols usually do not employ authentication in controlling messages, which give opportunity to adversaries. Thus adversaries are free to alter the information in control messages. Vampire attackers can take advantage of the above mentioned features and organize attacks in the form of [110]:

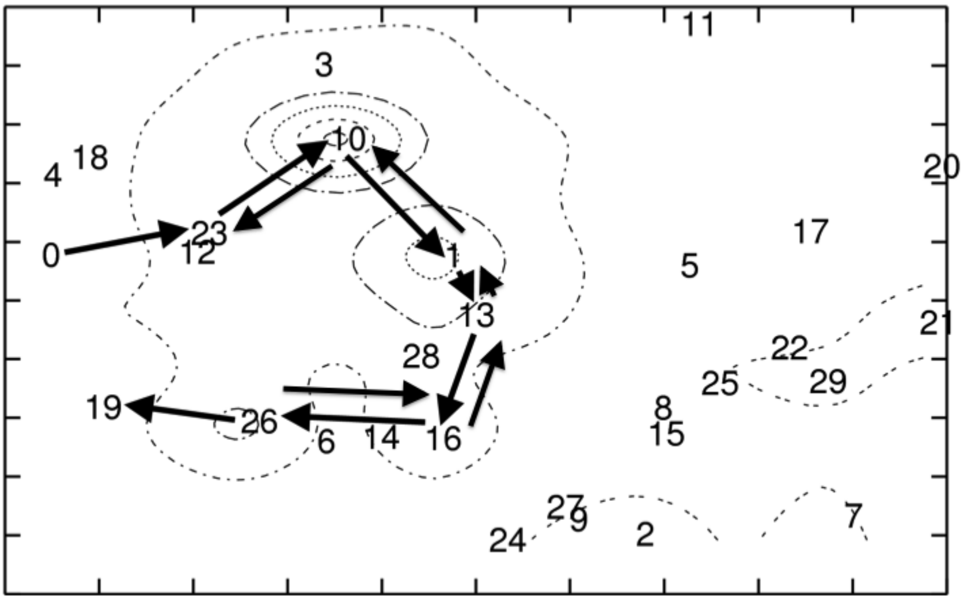


Fig. 2.5 Example: route loop attack (carousel attack)

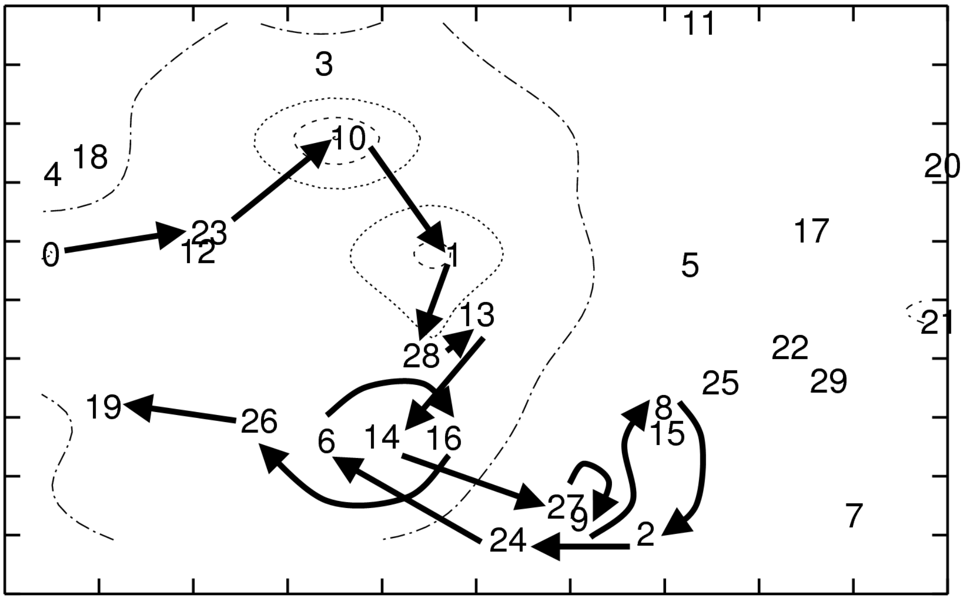


Fig. 2.6 Example: stretch attack

- Route loop attack (carousel attack): as shown in Figure 2.5, in this attack pattern, an adversary purposely introduces routing loops and makes the same data packet travel repeatedly through the same group of nodes.

- Stretch Attack: as illustrated in Figure 2.6, in this attack pattern, an adversary tries to establish unnecessarily long routes, potentially passing through as many as possible nodes in the network. We call this the stretch attack because it increases average route length, forcing packets to be received and forwarded by a number of nodes that are initially not supposed to participate.

To the best of our knowledge, there has been very little discussion on the prevention against the Vampire attacks. The existing proposed solution, such as PLGPa [110], a modified version of PLGP (clean-slate secure sensor network routing protocol) [78], highly rely on cryptographic methods, which can incur extra computation and transmission cost. Considering the limited computing capability and energy storage of wireless sensors, better (meaning more energy efficient and requiring less hardware) mitigation scheme is worth investigating.

2.7 Summary

In this chapter, previous works on WSN routing protocols with various concerns have been reviewed. Furthermore, the security challenges for WSNs, together with the existing countermeasures and potential opportunities were presented as well.

Chapter 3

AODV-EHA: Energy Harvesting Aware Routing Protocol

3.1 Introduction

As addressed in Section 2.1, one limitation of traditional routing attempts for WSNs is that they just try to cope with either of two features, namely, WSN's ad hoc nature and the utilization of energy harvesting technology in WSNs. Therefore, in this chapter, we propose the AODV-EHA that not only inherits the advantage of existing AODV on dealing with WSN's ad hoc nature, but also make use of the energy harvesting capability of the sensor nodes in the network.

The rest of this chapter is organized as follows. Section 3.2 summarizes background knowledge and theoretical analysis of AODV-EHA and its competitors. Section 3.3 provides simulation results that illustrating the advantage of the proposed routing protocol. The summary and further issues are in Section 3.4.

3.2 Comparison of AODV-EHA and Competitors

3.2.1 Overview of Original AODV Routing Protocol

As stated in [80], the network that adopts AODV is silent until a connection is requested. After that the sender (or source) node that needs a connection broadcasts a Route Request (RREQ) for connection. Other nodes in the network forward this message, and record the node that they heard it from, creating temporary routes back to the sender node. When a node receives such a message and already has a route to the desired receiver (or destination) node, it sends a Route Reply (RREP) backwards through a temporary route to the requesting node. The sender node then adopts the route with least hops through other nodes.

Eventually, the original AODV protocol attempts to figure out the route with least communication hops from any source node to the destination node. In other words, suppose the total number of possible routes in between is N_r and along any i-th route (i is an integer and $1 \leq i \leq N_r$) there are J_i nodes, if the k-th route is the optimal one determined by AODV, then it satisfies J_k=min$[J_1, J_2, ..., J_{N_r}]$.

3.2.2 Overview of DEHAR

As mentioned in Section 3.1, the basic idea of DEHAR is to introduce a new concept of "energy distance". The energy distance between a certain sender node and its receiver node can be considered as a weighted spatial distance that is related to the current energy status (how much energy could be harvested from ambient) of the sender. Assume along any i-th route, the total energy distance $D(i)$ is defined as

$$D(i) = D(i,1) + D(i,2) + ... + D(i, J_i - 1) \tag{3.1}$$

Suppose m is an integer and $1 \leq m \leq (J_i - 1)$, thus $D(i,m)$ is the energy distance from node m to $m+1$ and $D(i,m) = d(i,m) + f[\alpha(i,m)]$, where $d(i,m)$ is the spatial distance between node m and $m+1$ on the i-th route, $\alpha(i,m)$ is the energy could be

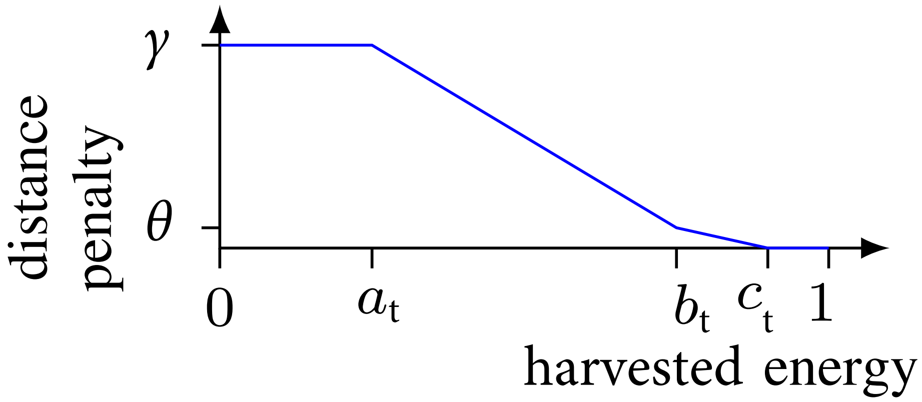


Fig. 3.1 Relation between energy availability and distance penalty

harvested and used for data transmission at m-th node that is defined over $[0,1]$ (normalized with respect to the energy required for transmission). The function $f[\alpha(i,m)]$ can be considered as "distance penalty" (more harvested energy refers to less distance penalty and vice-versa) and defined as:

$$f[\alpha(i,m)] = \begin{cases} 0 & , \quad 1 \geq \alpha_{im} > c_t \\ \theta^{\frac{\alpha(i,m)-c_t}{b_t-c_t}} & , \quad c_t \geq \alpha_{im} > b_t \\ (\gamma-\theta)\frac{\alpha(i,m)-b_t}{a_t-b_t}+\theta & , \quad b_t \geq \alpha(i,m) \geq a_t \\ \gamma & , \quad a_t > \alpha(i,m) \geq 0 \end{cases} \tag{3.2}$$

where a_t, b_t and c_t are different thresholds of energy that can be harvested for data transmission. As already defined in [42], c_t determines the upper bound for sensitivity, a_t is the lower bound for energy availability, and b_t describes the point of change between different sensitivities of variations in energy availability. Further, θ and γ are the penalty amplitude and maximum penalty, respectively. The author provides a chart showing an example of relation between energy availability and distance penalty in Figure 3.1 (in this example $a_t = 0.25$, $b_t = 0.75$, $c_t = 0.9$, $\gamma = 50$, $\theta = 5$).

As illustrated in Figure 3.1, in order to add energy awareness, $\alpha(i,m)$ is converted into a distance penalty $f[\alpha(i,m)]$. $f[\alpha(i,m)]$ is monotonically decreasing, where the ideal situation is that $f[\alpha(i,m)]$ approaches zero when there is plenty of energy, i.e.

```
  0                   1                   2                   3
  0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |     Type      |R|A|    Reserved     |Prefix Sz|   Hop Count   |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                     Destination IP address                    |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                  Destination Sequence Number                  |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                    Originator IP address                      |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                           Lifetime                            |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Fig. 3.2 RREQ message format in original AODV [80]

$f[\alpha(i,m)] \rightarrow 0$, when $\alpha(i,m) \rightarrow 1$, and $f[\alpha(i,m)]$ approaches maximum penalty γ when there is lack of energy, i.e. $f[\alpha(i,m)] \rightarrow \gamma$, when $\alpha(i,m) \rightarrow 0$.

The optimal route (denoted by the k-th route) determined by DEHAR satisfies the condition $D(k) = min[D(1), D(2), ..., D(N_r)]$. Note that after all the spatial distance are encoded to “energy distance”, DEHAR calculates the shortest energy distance by using existing method such as Directed Diffusion.

3.2.3 New AODV-based Routing Approach: AODV-EHA

As mentioned in Section 3.1, the AODV-EHA utilizes the advantages of original AODV together with the promising energy harvesting simultaneously: not only adapted to the ever changing network topology (the entire network does not need to be known by the routing algorithm in advance), but also achieving energy efficiency for a longer network lifetime. All these features are achieved by making full use of the existing mechanism of AODV without extra complexity and routing overhead.

Suppose that a process at source node wants to send a packet to destination node, the AODV-EHA algorithm maintains an energy vector table at each node in the network, keyed by destination, giving information about that destination, including the neighbour to which to send packets to reach the destination. First, source node looks in its table. If the source node does not find an entry for destination, it has to discover a route to destination node. This property of discovering routes only when they are needed is what makes this algorithm “on-demand”.

To locate destination node, the source constructs a RREQ packet and broadcasts it using flooding. Note that the RREQ format of AODV-EHA is different from that of the original AODV (Figure 3.2 [80]). In AODV-EHA, the field "hop count" is replaced with "energy count". "Energy count" here implies the prediction of average transmission cost to successfully deliver a data packet from the originator node to the node handling the request. The prediction details are stated in Equation (3.3 – 3.7) later in this chapter. The RREQ transmissions from source node reach its neighbours, each node rebroadcasts the request, which continues to their neighbour nodes. A sequence number set at the source is used to weed out duplicates during the flood.

Eventually, the request reaches destination node, which constructs a RREP packet. Note that the same change made in RREQ applies to RREP message as well in AODV-EHA: the field "hop count" is replaced with "energy count", but the "energy count" here denotes the prediction of average transmission cost to successfully deliver a data packet from the originator node to the destination node. Afterwards this RREP packet is unicast to the sender along the reverse of the path followed by the request. For this to work, each intermediate node must remember the node that sent it the request. Each intermediate node also increments certain "energy count" as it forwards the reply. This tells the nodes how much energy is needed to reach the destination. The replies tell each intermediate node which neighbour to use to reach the destination: it is the node that sent them the reply. Intermediate nodes put the best route they hear into their routing tables as they process the reply. When the reply reaches source node, a new route that can reach destination node, has been created.

Therefore, unlike the original AODV described in Section 3.2.1, the proposed AODV-EHA intends to find out the route with least expected transmission cost rather than least hop count. The practical operation of AODV-EHA is similar to original AODV except for small changes are in the formation of the corresponding messages, e.g. RREQs and RREPs.

Since the original AODV routing protocol sends these messages (RREQ, RREP, etc.) in the route discovery process, there is no additional routing overhead in AODV-EHA.

In the rest of this subsection, the analysis on transmission cost prediction in AODV-EHA is presented.

On any chosen i-th route, the expected total transmission cost $E(i)$ in terms of energy can be calculated as

$$E(i) = E(i,1) + E(i,2) + ... + E(i,J_i - 1) \tag{3.3}$$

where $E(i,m)$ denotes the estimation of transmission cost from the m-th node on this route to its next hop ($1 \leq m \leq J_i - 1$). Transmission cost depends on successful delivery of a packet possibly after a number of reattempts. To be more specific, transmission cost has the form

$$E(i,m) = K(i,m)\,[P(i,m) + P_c + P_r]\,t \tag{3.4}$$

where $K(i,m)$ is the predicted average number of retries after a packet is successfully transmitted from node m to its next hop node $m+1$; $P(i,m)$ is the minimum required radio transmission power level at node m to successfully deliver a data packet to the next hop; P_c is the processing power at node m (consumed by circuits of the node for the preparation of radio transmission, e.g. coding, modulation); P_r is the receiving power at next hop $m+1$ (consumed for receiving data, e.g. demodulation, decoding); and t is the transmission time needed for delivering a packet.

Some of the nodes are assumed to be capable of harvesting energy from the surrounding environment. The harvested energy is considered as free and accounted in $E(i,m)$ as

$$E(i,m) = K(i,m)[P(i,m) + P_c + P_r - \alpha(i,m)R]t \tag{3.5}$$

where R is the maximum output power of the photo-voltaic power generator, and $\alpha(i,m) = 0$ if node m is without energy harvesting or $\alpha(i,m)$ is a random number defined over $[0,1]$ if node m has energy harvesting. As addressed in Section 3.1, for the applications under consideration, solar cells are more suitable to be mounted on sensor nodes considering the size (e.g. wind driven generator is too bulky) or energy source accessibility (e.g. motion power is hard to access since nodes operate in severe environment where human activity is rare).

For these nodes, $\alpha(i,m) = R^{'}/R$ where $R^{'}$ is the active power level of the photo-voltaic power generator. For a photo-voltaic power generator [47], its active power is assumed to follow a $\beta-$distribution given by the following probability density function:

$$F(R^{'}) = \frac{\Gamma(p_{sh}+q_{sh})}{\Gamma(p_{sh})\Gamma(q_{sh})}\left(\frac{R^{'}}{R}\right)^{p_{sh}-1}\left(1-\frac{R^{'}}{R}\right)^{q_{sh}-1} \tag{3.6}$$

where p_{sh} and q_{sh} are the shape parameters of the distribution, and Γ is the Gamma function. Beta distributions are fit to the past record of sunlight data using the algorithm that minimizes the K–S statistic [23], and its shape parameters p_{sh} and q_{sh} depend on the specific geographic location where sunlight data are recorded. This assumption is also based on the past recorded sunlight data and statistical correlation analysis of solar radiance and consumer load.

From [53], in order to successfully transmit a packet from node m to its next hop node $m+1$, the expected average number of retries $K(i,m)$ can be calculated as

$$K(i,m) = \frac{1}{1-\mathscr{P}_{out}(i,m)} \tag{3.7}$$

where $\mathscr{P}_{out}(i,m)$ is the probability of the packet not been delivered (or outage probability) from node m to node $m+1$ on any attempt. Based on the previous work in [95], $\mathscr{P}_{out}(i,m)$ can be expressed as a function in $P(i,m)$.

Eventually the optimal route (denoted by the k-th route) determined by proposed AODV-EHA satisfies that $E(k) = \min\ [E(1),E(2),...,E(N_r)]$.

3.3 Performance Evaluation

In this section, the performance of original AODV, AODV-EHA and the DEHAR protocols are analysed under MATLAB platform. The word "performance" here implies:

- Average transmission cost between any two arbitrary nodes within the network after a data packet is successfully delivered.
- Average hop count of the route (may be determined by any routing protocol) where the data packet travelled through between those two arbitrary nodes.

Then the performance of these three routing approaches are compared and the relationship between them is revealed.

3.3.1 Route Discovery in Simulator

The simulator utilizes Dijkstra algorithm [24] to determine the optimal route under different routing protocols. Dijkstra algorithm was originally designed for finding the shortest paths between nodes in a graph, and the "shortest" here implies shortest distance. If we replace the factor "distance" for other metrics, e.g. "hop count" (for AODV), "energy distance" (for DEHAR), and "energy count" (for AODV-EHA), Dijkstra can be utilized to find the optimal route as if AODV or DEHAR or AODV-EHA is adopted. Of course, the practical operation of these 3 protocols in real world are different, but the eventual results (determined optimal routes) are the same.

Some simple examples of the optimal routes determined by AODV, DEHAR and AODV-EHA using the simulator are illustrated in Figure 3.3 – 3.5: 50 nodes are randomly distributed in the fixed simulation area (500 $m \times 500$ m), normal nodes are denoted by black dot with node number, nodes with energy harvesting capability are denoted by green dot with node number. Suppose the objective is to find a route from node *41* to node *31*. The estimated energy consumption to deliver a single packet along *41* → *31* determined by AODV (with least hop count) is approximately 0.000612 Joule; meanwhile that of DEHAR and AODV-EHA along *41* → *31* (longer route but least transmission cost) are approximately 0.000608 Joule and 0.000491 Joule, respectively.

A few simple examples are far from enough, thus the simulations using Monte-Carlo approach are performed: certain number of nodes are randomly distributed in the fixed simulation area, pick any one of them and evaluate the performance under the 3

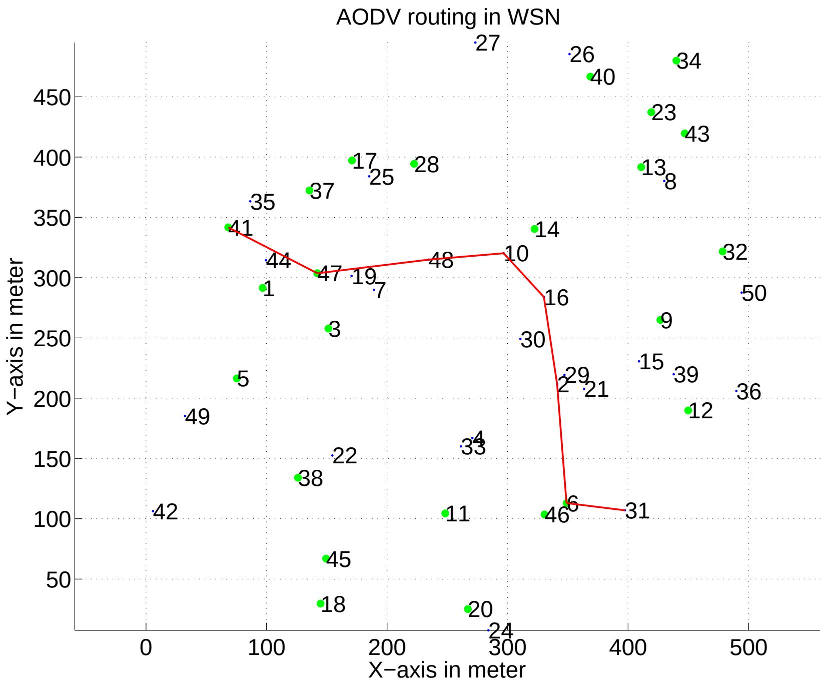


Fig. 3.3 A simple example: route Determined by AODV

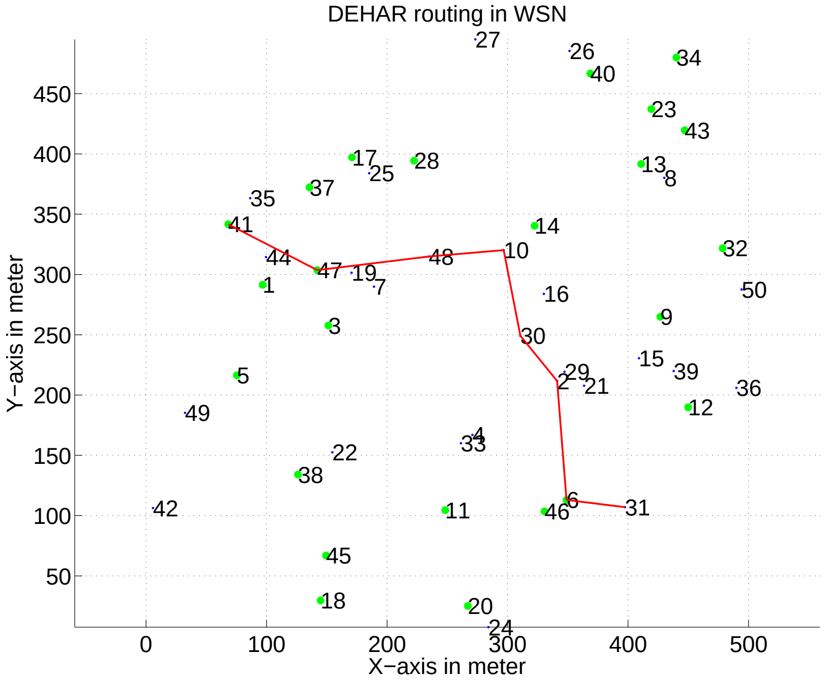


Fig. 3.4 A simple example: route determined by DEHAR

different routing protocols when delivering a data packet back to a specific destination node. Repeat this process for a large enough number of times, then evaluate average performance of the three routing protocols.

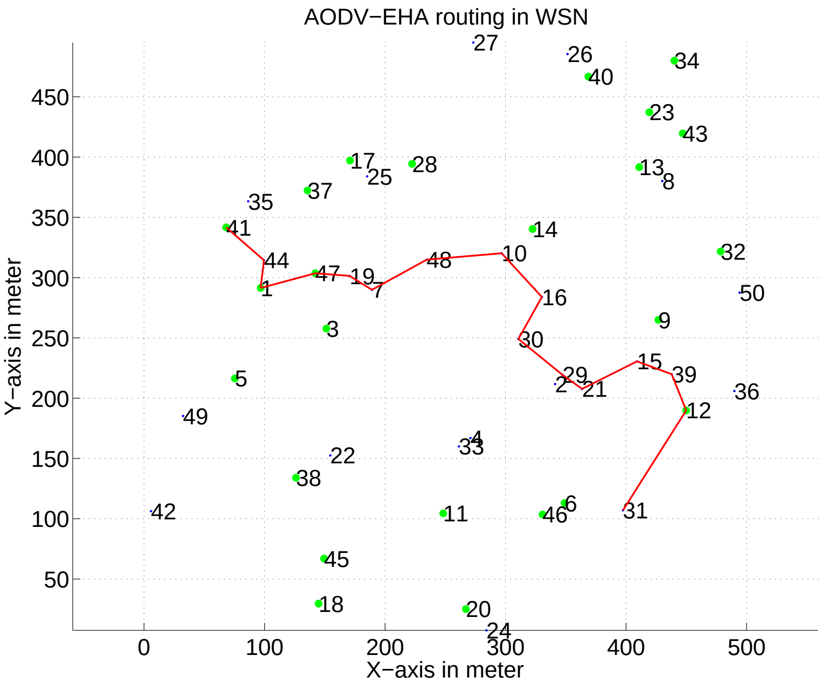


Fig. 3.5 A simple example: route determined by AODV-EHA

3.3.2 Simulation Setup

IEEE 802.15.4 is a leading standard that is widely used in WSNs, this standard focuses on low data-rate, and low-power ubiquitous communication among devices [39, 114]. According to the specification mentioned in [39], lower data rates of 20 and 40 kbps were initially defined, with maximum 250 kbps rate being supported in the current revision [115]. Lower data rates bring not only less power consumption, but also lower manufacturing cost and technological simplicity, without sacrificing flexibility

Table 3.1 Simulation setup

Parameters	Descriptions
Simulation Area	500 m × 500 m
Node Radio Range	250 m
Traffic Type	CBR
Packet Size	127 bytes
Data Rate	20 kbps
Threshold β	10
Processing Power Level P_c	10^{-4} W
Receiving Power Level P_r	5×10^{-5} W
Outage Requirement $\mathscr{P}^*_{out}(i,m)$	10^{-4}

or generality. The medium access control (MAC) enables the transmission of MAC frames through the use of the physical channel. Note that the IEEE 802.15 standard does not utilize 802.1d or 802.1q, in other words, standard Ethernet frames cannot be exchanged. The physical frame-format is specified in [39], and it is tailored to the fact that most IEEE 802.15.4 PHYs only support frames of up to 127 bytes (since the frame is generally composed of frame header, payload data from upper layer and frame footer, thus this limitation can affect some settings in upper layer, such as packet size in network layer).

As mentioned above, if we choose IEEE 802.15.4 for the physical and data link layer, which is suitable for the nominated WSN applications in this dissertation (low data rate but very long battery life), the settings of data rate and packet size in simulations are confined by this choice. Therefore, in all our simulations we assume the traffic type is constant bit rate (CBR) with a data rate of 20 Kbps and the packet size is 127 bytes, as illustrated in 3.1. Note that lower data rate means longer transmitting time, lower transmission power level and longer processing time when a node is sending data packets. On the other hand, larger packet size means longer transmission time for delivering a packet. Therefore, the choice of data rate and packet size can affect the calculation of expected transmission cost along a specific route (details can be found in Section 3.2.3). As a result, when we are simulating route discoveries in AODV-EHA, the metric “energy count” (see Section 3.3.1 for details) used in the simulator can be affected by the settings of data rate and packet size, and this may influence the final result of optimal route under AODV-EHA. In addition, the transmission cost evaluations (later addressed in Section 3.3.3) can be influenced by these settings as well.

Other parameters also can be found in Table 3.1: for each single hop transmission, P_c denotes the data processing power consumed by a transmitting node, receiving node consumes P_r power units to receive the data. The values of the parameters P_r , P_c and the communication range of each node are assumed the same for all nodes in the network and are specified by the manufacturer. Outage requirement $\mathscr{P}^*_{out}(i,m)$ is defined as the maximum tolerated probability that the received SNR at receiving node falls below a certain threshold β. If the received SNR is higher than the threshold β, the receiver is assumed to be able to decode the received message with negligible probability of error. If an outage occurs, the packet is considered lost. The SNR threshold β is determined according to the application and the transmitter/ receiver structure.

3.3.3 Simulation Results

The simulations use Monte-Carlo approach considering two typical simulation scenarios:

Scenario 1: stationary destination node.

This scenario can be considered as the application of environment surveillance. The engineer just stays at a fixed observation point in the region where the WSN is deployed, and collects data from the nodes. The number of nodes varies from 10 to 90.

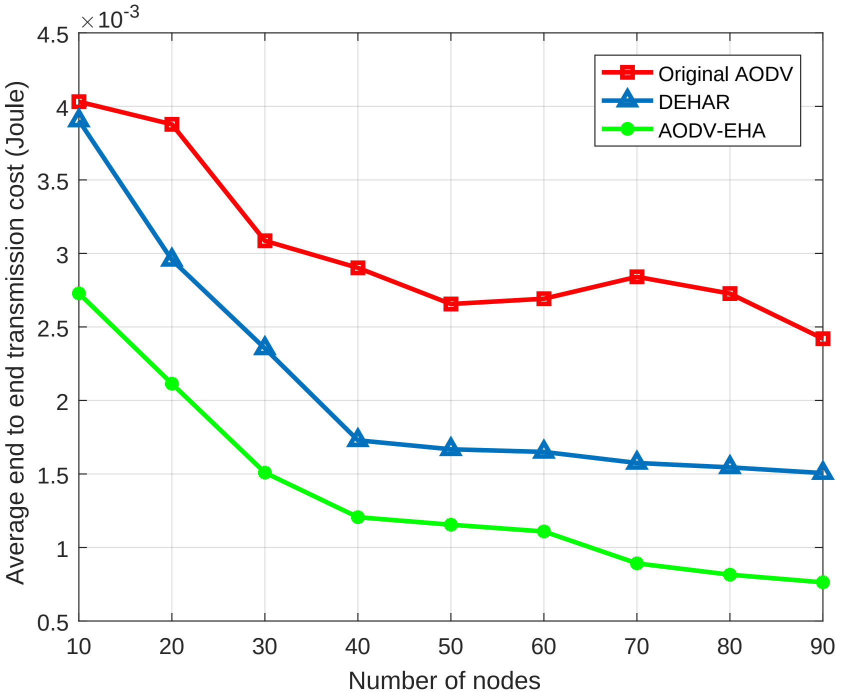


Fig. 3.6 Average transmission cost versus the number of nodes

Figure 3.6 compares the average end-to-end transmission cost of original AODV, DEHAR and AODV-EHA, after a data packet is successfully delivered. Figure 3.7 – 3.8

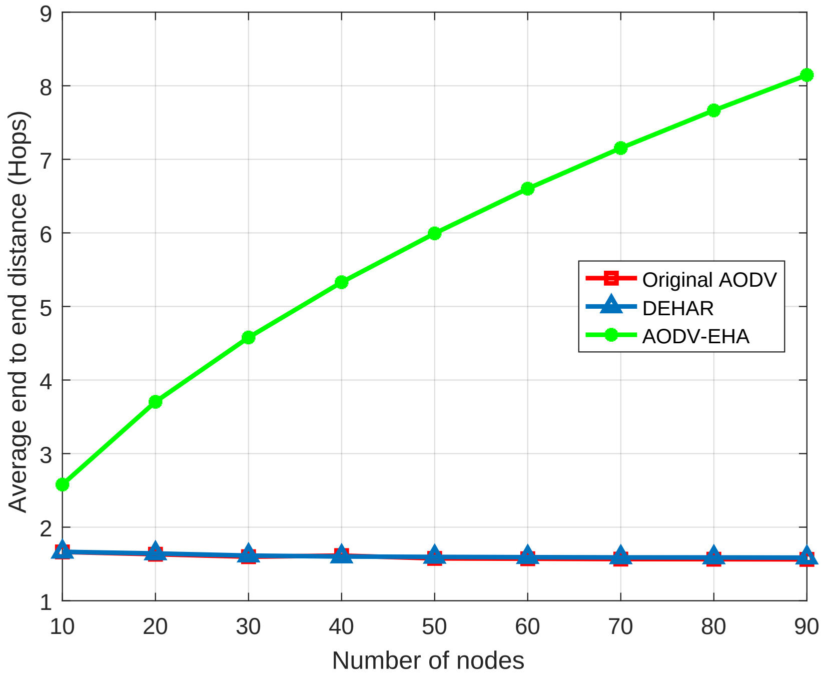


Fig. 3.7 Average route length (hop count) versus the number of nodes

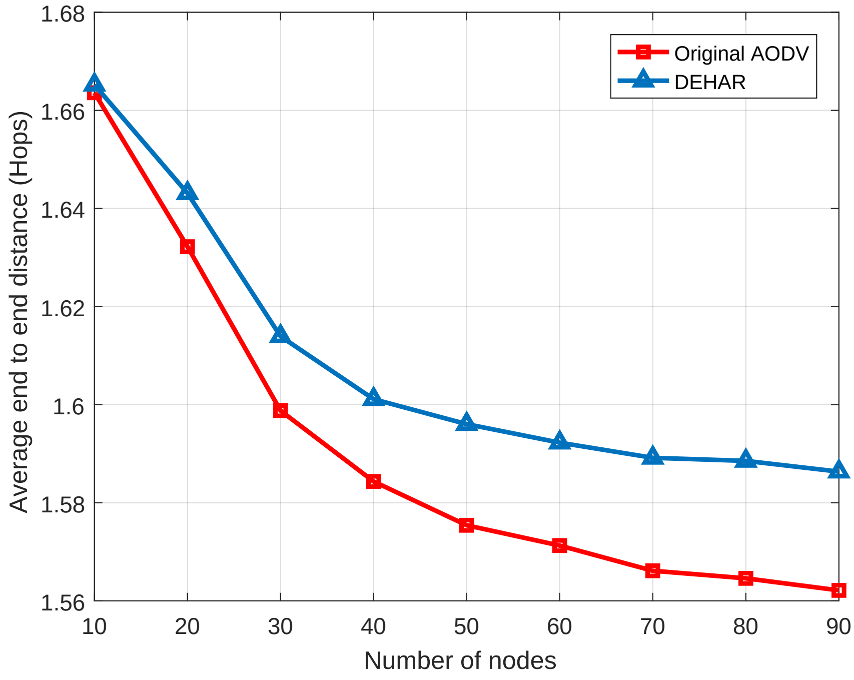


Fig. 3.8 Average route length (hop count) versus the number of nodes

show the average end-to end route length (hops) of the original AODV, DEHAR and AODV-EHA protocols.

From Figure 3.6, we can conclude that as the number of nodes increase, both the average transmission cost of AODV-EHA and DEHAR decrease gradually, and AODV-EHA overcomes DEHAR in any case in terms of energy saving. By contrast, the same records of original AODV fluctuate along with the nodes number increases, and showing an apparent descending tendency, but shows more cost compared to that of DEHAR and AODV-EHA in all instances. The fluctuation of energy cost using AODV is because the AODV is seeking for the route with least hops, but less hops does not always bring less energy cost in wireless transmissions, as been discussed before [95]. Note that lower transmission cost means less energy consumption for all the nodes involved in transmission, that is, given a same battery capacity, the nodes are expected to operate a longer time and send more data. Therefore the network lifetime can be prolonged as well. For example, when the nodes number is 50, the nodes in the network adopting AODV-EHA are expected to send approximately 44.42% more data packets at most (compare to the adoption of DEHAR).

On the other hand, under AODV-EHA, the route length is increasingly high as the number of nodes in the area goes up, while that of original AODV and DEHAR are slightly reduced, as can be seen from 3.7 (the results of original AODV and DEHAR are further presented in Figure 3.8 that otherwise their difference cannot be seen clearly). A longer route length may lead to longer end-to-end delay, but normally it should not be a problem in this scenario, e.g. meteorological observation frequency is normally at minute level [57].

Scenario 2: destination node with mobility.

This scenario can be considered as the application of enemy detection in the battlefield. An engineer (or data collecting device) can be assigned to any position in the area where WSN is deployed, not tied a fixed place as in scenario 1. In the same way as in scenario 1, the Monte-Carlo approach is adopted except the only difference is the position of data collecting point is random instead of stationary. The number of nodes varies from 10 to 90.

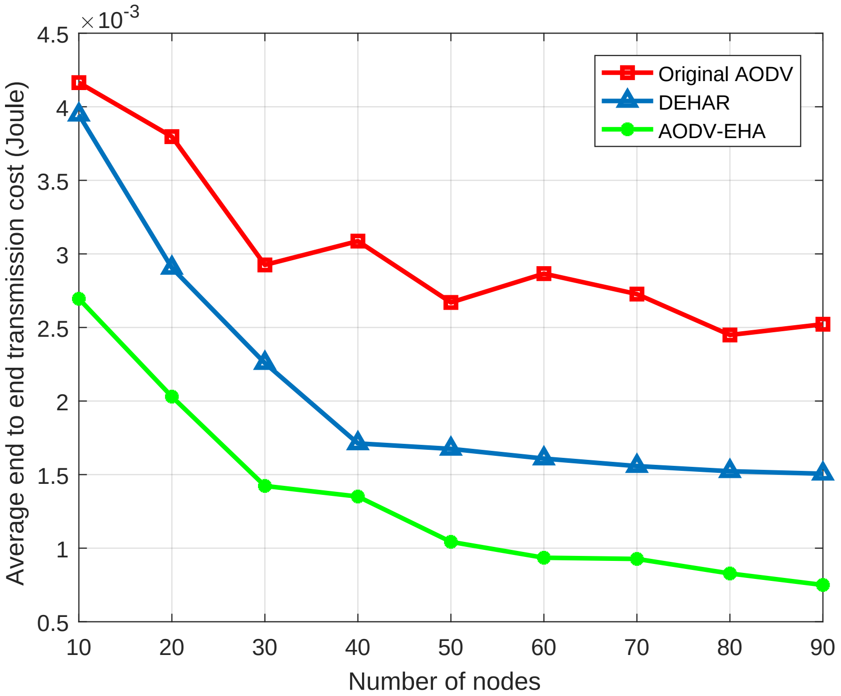


Fig. 3.9 Average transmission cost versus the number of nodes

Figure 3.9 compares the average end-to-end transmission cost of original AODV, AODV-EHA and the DEHAR, after a data packet is successfully delivered. Figure 3.11-3.10 show the average end-to end route length (hops) of the original AODV, DEHAR, and AODV-EHA protocols.

From Figure 3.9, we can conclude that as the number of nodes increase, the average transmission cost of AODV-EHA and DEHAR decrease gradually, and AODV-EHA overcomes DEHAR in any case in terms of energy saving. By contrast, the same records of original AODV fluctuate along with the nodes number increases, and showing an unapparent descending tendency, but has more cost compared to that of DEHAR and AODV-EHA in all instances.

On the other hand, under AODV-EHA, the route length is increasingly high as the nodes number in the area goes up, as can be seen in Figure 3.10 (the results of original AODV and DEHAR are further presented in Figure 3.11 that otherwise their difference cannot be seen clearly). Longer route length may lead to longer end-to-end delay, which could negatively affect time sensitive applications such as the one in this scenario. Thus before making the decision, the exact delay-tolerance level, energy

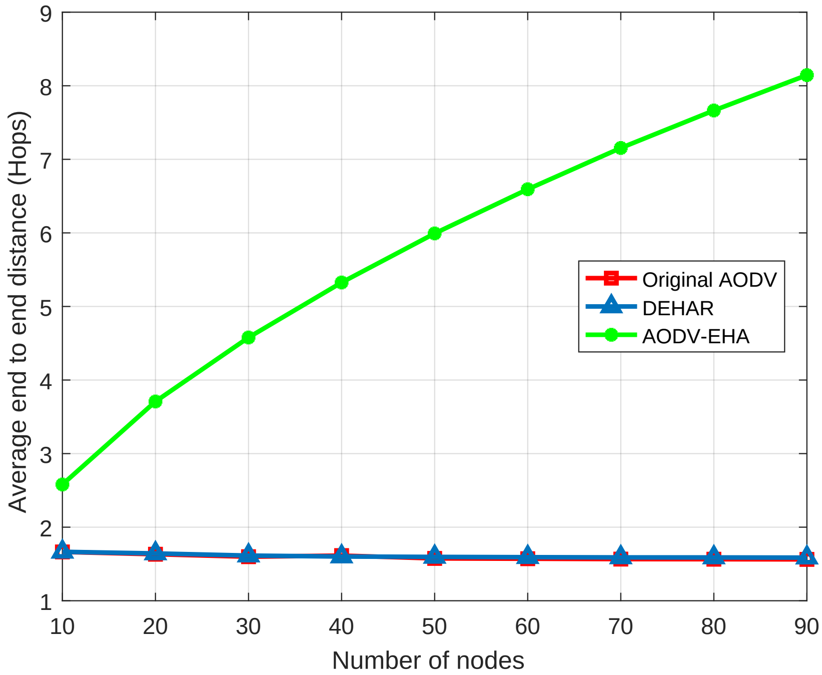


Fig. 3.10 Average route length (hop count) versus the number of nodes

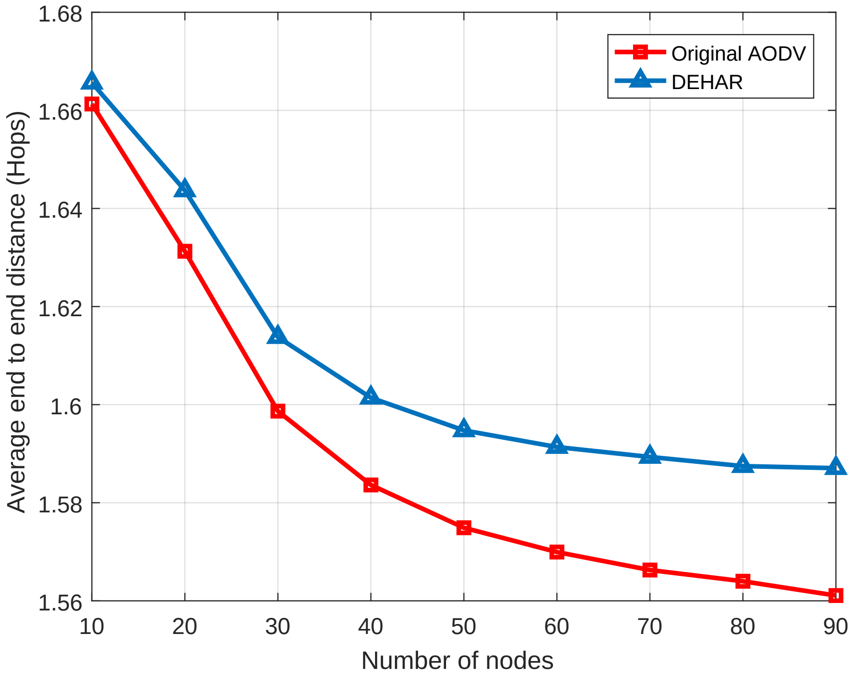


Fig. 3.11 Average route length (hop count) versus the number of nodes

consumption requirement, nodes distribution density, etc., for practical situation should be carefully evaluated, and see which routing protocol will be the best trade-off between those factors concerning.

3.4 Summary

In this chapter, we introduced the AODV-EHA routing protocol for environmental, military, or commercial WSN applications. In these applications, nodes are usually deployed without careful pre-planning and are not static after initial deployment. Meanwhile nodes are energy sensitive since they usually work in severe environment and battery replacement are usually not possible. AODV-EHA not only inherits the advantage of existing AODV on dealing with WSN's ad hoc nature, but also makes use of the energy harvesting capability of the sensor nodes in the network. Consequently, AODV-EHA achieved both energy efficiency and capability of handling network topology change. Through simulations, we evaluated the performance of original AODV, AODV-EHA and the DEHAR routing protocols. Although AODV-EHA usually finds the longest routing paths, it has the smallest transmission overhead along the determined routes.

Chapter 4

ETARP: An Energy Efficient Trust-Aware Routing Protocol

4.1 Introduction

While routing protocols have been proposed for either energy efficiency or security, as been discussed in Chapter 2, the new routing protocol proposed in this chapter balances these two concerns simultaneously by means of utility theory. To the best of our knowledge, this is an original approach for WSN routing protocols. An essential component of the routing protocol is the method to estimate energy consumption for packet forwarding. Another essential element is a Bayesian network to judge the probability of each node being compromised (which serves as a measure of trust or reputation).

The rest of this chapter is organized as follows. Section 4.2 gives the background knowledge on utility theory together with a few related work. Section 4.3 presents the central concepts in the new ETARP. The methods used to estimate energy consumption and risk of node compromise are explained. Performance evaluation in terms of simulation results is presented in Section 4.4. Section 4.5 summarize this chapter.

4.2 Essentials to Utility Theory

4.2.1 General Concept

Utility is a quite general concept known from microeconomics. Many classical books on economics have addressed the field of utility theory exhaustively, such as [65] by Mankiw and [108, 109] by Varian. In the rest of this subsection, some parts of the utility theory that are closely related to this dissertation are given.

Economists in Victoria days used utility as a numeric measure of the term “satisfaction” or “happiness”, normally the utility was sensitive to the price and quantity of the goods. Given this idea, it was natural to think of consumers making choices so as to maximize their utility, that is, to make themselves as happy as possible.

The drawback of this idea is that how to exactly measure the utility is not really described by these economists, then some consequent questions arise: is one person’s utility the same as another person’s? What is the meaning to say that an extra bottle of coke-cola would give somebody twice as much utility as an extra cup of apple juice? Does the concept of utility have any independent meaning other than its being what people maximize?

Due to these conceptual problems, modern economists have abandoned the old-fashioned view of utility as being a measure of happiness. Instead, the theory of consumer behaviour has been reformulated entirely in terms of “consumer preferences”, and utility is seen only as a way to describe preferences. Economists gradually began to recognize that all that mattered about utility as far as choice behaviour was concerned was whether one commodity had a higher utility than another—how much higher did not really matter. Originally, preferences were defined in terms of utility: to say a commodity x was preferred to a commodity y meant that the x-commodity had a higher utility than the y-commodity. But now we tend to think of things the other way around. The preferences of the consumer are the fundamental description useful for analysing choice, and utility is simply a way of describing preferences.

The only property of a utility assignment that is important is how it orders the commodities. The value of the utility is only important insofar as it ranks the different consumption commodities; the size of the utility difference between any two consumption commodities does not matter. Because of this emphasis on ordering commodities, this kind of utility is referred to as ordinal utility.

A utility function is a way of assigning a value to every possible consumption commodity such that more-preferred commodities get assigned larger numbers than less-preferred commodities. That is, a commodity x is preferred to a commodity y if and only if the utility of x is larger than the utility of y: in symbols, $x \succ y$ if and only if $u(x) > u(y)$.

Since only the ranking of the commodities matters, there can be no unique way to assign utilities to commodities. If we can find one way to assign utility numbers to commodities, we can find an infinite number of ways to do it, as long as they satisfy: $x \succ y$ if and only if $u(x) > u(y)$. If $u(x)$ represents a way to assign utility value to the commodity x, then multiplying $u(x)$ by 2 (or any other positive number) is just as good a way to assign utilities.

Multiplication by 2 is an example of a monotonic transformation. A monotonic transformation is a way of transforming one set of numbers into another set of numbers in a way that preserves the order of the numbers. If $f(u)$ is any monotonic transformation of a utility function that represents some particular preferences, then $f[u(x)]$ is also a utility function that represents those same preferences. Examples of monotonic transformations are multiplication by a positive number (e.g. $f(u) = 6u$), adding any number (e.g., $f(u) = u + 8$), raising u to an odd power (e.g. $f(u) = u^5$), and so on. This above discussion can be summarized by stating the following principle: a monotonic transformation of a utility function is a utility function that represents the same preferences as the original utility function.

4.2.2 Utility Theory Applied in Network Research

In network research, utility usually refers to the satisfaction the network user derives from obtaining the service provided by the network. Initiated by the work of [50] on network utility maximization (NUM), utility theory has been extensively employed for certain directions in network research. Previous researches conclude that utility theory is one of the most popular choices applied on resource allocation [22, 105] and network selection [111] in wireless networks. In rest of this subsection we highlight some of the utility-based network researches.

In [19], a centralised, utility-based resource allocation scheme for mixed traffic in wireless networks is proposed. In this paper, the unified utility function for users with different traffics is studied first. After that, the optimization model for the resource allocation is established based on the unified utility function. A heuristic algorithm based on the solution of the model is proposed in the mixed traffic scenario after analysing the optimization model. The algorithm which has lower complexity than the existing work can automatically guarantee the QoS requirement for the real-time traffic and make a trade-off between throughput and fairness for users with best effort traffic due to the unified utility function.

The authors in [74] focus on utility models in the context of access network selection. In this paper, the utility theory is adapted and consolidated to define an appropriate decision mechanism in the frame of the access network selection. Subsequently, they propose single-criterion and multi-criteria utility forms to best capture the user satisfaction and sensitivity facing up to multiple access network characteristics (e.g. cost, QoS, and network load).

In [12], utility theory and bankruptcy game are applied in joint bandwidth allocation for heterogeneous integrated wireless networks, by combining throughput and cost utilities for network selection and resource allocation. The proposed bandwidth allocation scheme consists of two successive stages, namely, service bandwidth allocation and user bandwidth allocation. Note that this paper assumes that monetary costs on the user imposed by different access networks are non-identical.

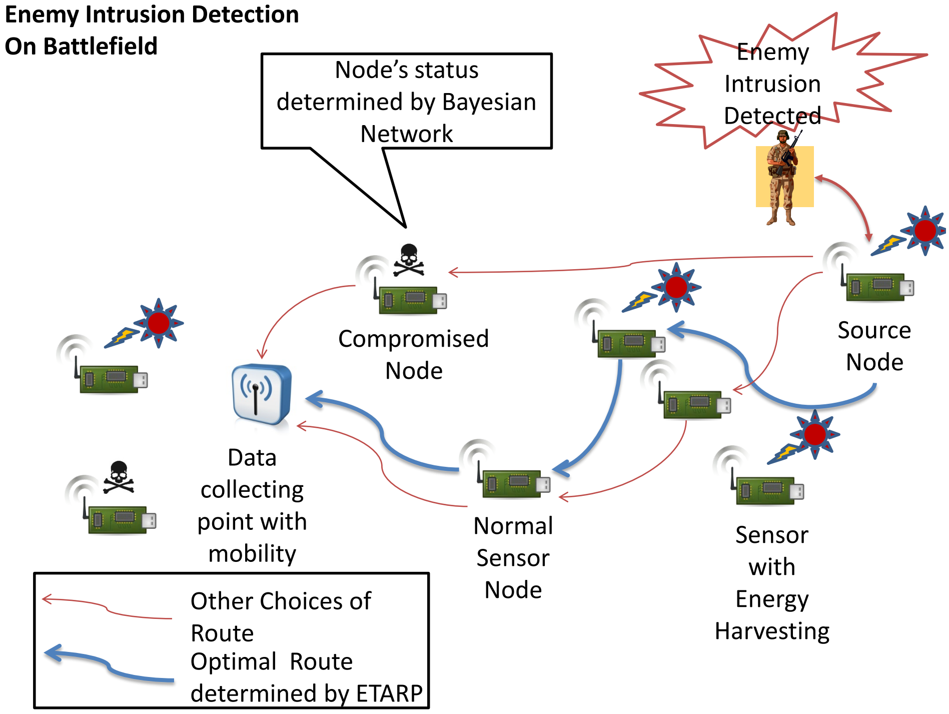
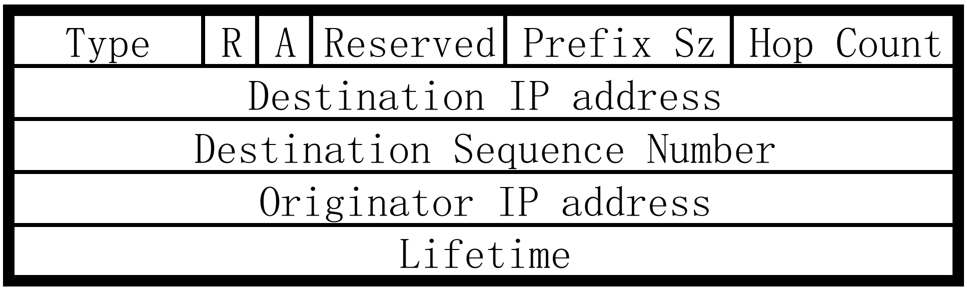

Enemy Intrusion Detection
On Battlefield
Node's status determined by Bayesian Network
Enemy Intrusion Detected
Compromised Node
Source Node
Data collecting point with mobility
Normal Sensor Node
Sensor with Energy Harvesting
Other Choices of Route
Optimal Route determined by ETARP

Fig. 4.1 Example of WSN application scenario

4.3 ETARP Routing

This section describes the ETARP routing protocol designed for the WSN applications mentioned in Chapter 1. The routing protocol aims to simultaneously consider energy efficiency and security to avoid routes that are inefficient and risky. In order to simplify the description, we assume for the moment a "normal" condition absent of attacks in the network. In this case, ETARP works to discover and select the most energy efficient routes. In the next section, attacks on the network will be taken into account to show how ETARP factors trustworthiness of nodes into the route selection. Because energy efficiency and security are two different problems, ETARP takes a novel approach of factoring both using the notion of expected utility.

A basic example to demonstrate the idea of ETARP is shown in Figure 4.1. After the enemy appears in the WSN covered region, their activity can be detected by a nearby sensor node (e.g. acoustic or seismic sensor) which will send warning information back to the data collection point. Usually this process cannot be accomplished in a single hop transmission. ETARP aims to find the most energy efficient multi-hop route while simultaneously avoiding any (perceived) compromised nodes. The status of nodes is



<table>
<tr><td>Type</td><td>R</td><td>A</td><td>Reserved</td><td>Prefix Sz</td><td>Hop Count</td></tr>
<tr><td colspan="6">Destination IP address</td></tr>
<tr><td colspan="6">Destination Sequence Number</td></tr>
<tr><td colspan="6">Originator IP address</td></tr>
<tr><td colspan="6">Lifetime</td></tr>
</table>

Fig. 4.2 RREQ message format in original AODV

estimated by a Bayesian network that collects data about observed node behaviors and calculates the probability that each node is compromised or not.

4.3.1 Energy Efficiency Routing in Absence of Attacks

For the moment, attacks on the network are ignored in order to present how ETARP operates to discover and select energy efficient routes. Previous studies have found that the ad hoc nature of the network dictates an on-demand routing protocol such as AODV. However, AODV aims to minimize hop count without consideration of energy costs. ETARP is based on AODV but adds awareness of transmission energy costs.

Route discovery by ETARP operates similarly to AODV except for a different format of the routing messages: RREQs, RREPs, and so on. The format of the RREQ message in the original AODV is shown in Figure 4.2 [80].

The same change applies to the RREP message as well. The field “hop count” in the original AODV RREP message is replaced with “energy count” in the ETARP RREP message.

Since ETARP uses the same basic messages (e.g. RREQ and RREP) as AODV, it does not incur more overhead compared to the original AODV. The next question is how to define energy consumption for the new “energy count” message field.

Similar to the definitions from Equation (3.3 – 3.7), on any chosen i-th route spanning a total number of J_i nodes, the expected total transmission cost $E(i)$ in terms of energy can be calculated as

$$E(i) = E(i,1) + E(i,2) + ... + E(i,J_i - 1) \tag{4.1}$$

where $E(i,m)$ is the estimated transmission cost from the m-th node on this route to its next hop ($1 \leq m \leq J_i - 1$). In specific, $E(i,m)$ has the form

$$E(i,m) = K(i,m)\,[P(i,m) + P_c + P_r]\,t \tag{4.2}$$

For nodes that are assumed to be capable of harvesting solar energy, $E(i,m)$ is rewritten as

$$E(i,m) = K_{im}[P(i,m) + P_c + P_r - \alpha(i,m)R]t \tag{4.3}$$

After ETARP discovers a number of possible routes, say with energy costs $\{E(1), E(2),$ $\ldots, E(N_r)\}$, it selects the route with the minimum energy cost.

4.3.2 Energy Efficient and Secure Routing in Presence of Attacks

The previous section dealt with the simple case of energy efficient routing assuming normal conditions without attacks on the network. The possibility of attacks adds complications because nodes can become compromised and interfere with packet forwarding.

Our approach to add security awareness into ETARP relies on the concept of "expected utility" from utility theory. Either transmission energy or risk of untrusted nodes will diminish the expected utility of a route. ETARP seeks routes with high expected utility which will be both energy efficient and trusted.

Definition of Utility in WSN

In WSNs, each node can be considered as a "customer", multiple choices of paths within the network that leads to destination node in data transmission represent the various "commodities" in the "market". And different route will bring different "consumer preferences", in other words, different utility, to a node that is scheduled to transmit data. Rather than "price" and "quantity", the utility or preference designated for a route is related to both energy cost and security level (trustworthiness).

Consider a specific route consisting of J nodes ($J-1$ hops). Considering only energy on any specific hop, say the m-th hop, the utility function is inversely proportional to the predicted transmission cost on this hop. Less energy consumption means a longer lifetime that is more "preferable" for the sensor nodes and therefore a higher utility. Then the utility function of the m-th hop, denoted by $u\left(\frac{1}{E_m}\right)$, satisfies

$$u\left(\frac{1}{E_m}\right) \propto \frac{1}{E_m} \tag{4.4}$$

where E_m (how to determine E_m can be found in Section 4.3.1) is the estimated transmission cost from the m-th node on this route to its next hop $(1 \leq m \leq J-1)$.

The transmission on each hop takes place successively over time, starting from the source node and ending at the destination node. The utility of all these hops are imperfect substitutes to each other, meaning that some reduction in utility of the m-th hop might be compensated for, to some extent, by the addition of another hop's utility and vice versa. But this is not always the case, e.g. if the m-th hop is a dead link, no matter how good condition the other hops are, this route is considered to be useless with zero total utility. Due to this imperfect substitutes property, the utility function of a specific route belongs to the Cobb-Douglas type with standard form of $U_{route} = u_1^{c_1} u_2^{c_2} u_3^{c_3} \ldots$, where $u_1^{c_1}, u_2^{c_2}, u_3^{c_3}, \ldots$ denote the utility generated from first, second, third, and so on until the last $(J-1)_{th}$ hop on a route, respectively. That is, the utility of a route is the product of utilities on all the $J-1$ hops [108]. On the other hand, wireless sensors deployed in a specific network typically belong to the same type with identical technical specifications, thus the sender nodes at each hop can be considered to be identical and use the same utility function to describe their "preference". In this case, the multiple $J-1$ hops transmission on this route can be considered as equivalent to a node repeating a single hop transmission $J-1$ times. Then the total utility on this route can be written as

$$U_{route}\left(\frac{1}{E_m}\right) = \prod_{m=1}^{J-1} u\left(\frac{1}{E_m}\right) = \prod_{m=1}^{J-1} \left(\frac{1}{E_m}\right)^{c_{ro}} \tag{4.5}$$

where c_{ro} is a positive constant indicating the "preference" level of each hop, which is related to the sensitivity to energy cost. Note that the numerator in the last part in (4.5) corresponds to the energy consumption factor on each hop, which is already explained in (4.3) of Section 4.3.1. As mentioned earlier in Section 4.2.1, $u\left(\frac{1}{E_m}\right) = \left(\frac{1}{E_m}\right)^{c_{ro}}$ is just one of the many ways to assign utility, there is an infinite number of ways to do it. Any functions, as long as they satisfy: $u\left(\frac{1}{E_{m_1}}\right) > u\left(\frac{1}{E_{m_2}}\right)$ (m_1, m_2 are integers and $m_1, m_2 \in m$) if and only if $\frac{1}{E_{m_1}} > \frac{1}{E_{m_2}}$, can be utilized to assign utility—including but not limited to logarithmic function (e.g. $u\left(\frac{1}{E_m}\right) = \log_2 \frac{1}{E_m}$) and exponential function (e.g. $u\left(\frac{1}{E_m}\right) = 2^{\frac{1}{E_m}}$). Some of the convex functions (e.g. $u\left(\frac{1}{E_m}\right) = e^{\frac{1}{E_m}}$) and concave functions (e.g. $u\left(\frac{1}{E_m}\right) = \log\frac{1}{\mathrm{E_m}}$) also can be valid choices as long as they are monotone increasing in their domains and can satisfy the above mentioned condition.

Calculation of Expected Utility

At each hop, there is a certain risk that the next node is compromised. In other words, there is never certainty about the status of any node (malicious or not). Given this uncertainty, we introduce the weighted average of utilities gained from all the possible results (malicious node or not) as the "expected utility" $u^{'}\left(\frac{1}{E_m}\right)$:

$$\begin{aligned} u^{'}\left(\frac{1}{E_m}\right) &= (H_m + (1-H_m)Q_m)\,u\left(\frac{1}{E_m}\right) + (1-H_m)(1-Q_m)0 \\ &= (H_m + (1-H_m)Q_m)\,u\left(\frac{1}{E_m}\right) \end{aligned} \tag{4.6}$$

where H_m is the probability that the destination node is safe (not compromised); and Q_m is the possibility that the destination node is compromised but pretends to behave like normal node (a so-called "grey hole"). How to determine the probability H_m is explained in Section 4.3.3. If the node is safe or pretending to be normal, the utility of this hop is $u\left(\frac{1}{E_m}\right)$. Otherwise the node is considered as compromised with zero utility. The total expected utility on the entire route is given by

$$U'_{route}\left(\frac{1}{E_m}\right) = \prod_{m=1}^{J-1} u'\left(\frac{1}{E_m}\right) \tag{4.7}$$

As mentioned earlier, utility is only useful for acting as an indicator of preference between different choices of routes, and the precise utility value does not have any practical meaning.

ETARP discovers a number of possible routes, along with their expected total utility. It selects the route with the maximum total utility as the best route.

4.3.3 Estimation of Risk by Bayesian Network

Generally it is difficult to ascertain whether a node has been actually compromised or not, unless it is manifested in the node's observable behaviour. A practical approach assumes that a risk can be estimated by observing the node's behaviour compared to its expected behaviour. In order to calculate a "belief" about a node's trustworthiness, a learning Bayesian network is proposed for this purpose. As mentioned in Section 2.4.5, unlike the reputation management employed by previously proposed AOTDV or LTB-AODV which only watch for a specific behaviour, a Bayesian network is meant to organize the entire knowledge about observed node behaviour into a coherent whole, and makes comprehensive judgements on node status. Another possible approach is to use joint probability distributions to deal with multiple types of nodes behaviours, but the size of a joint probability distribution would be exponential in the number of nodes behaviours of interest, increasing both modelling and computational difficulties. By contrast, a Bayesian network can address all of these difficulties in principle, by acting as a graphical modelling tool for specifying probability distributions [25].

To be more specific, a Bayesian network is a probabilistic graphical model that represents a set of random variables and their conditional dependencies via a directed acyclic graph (DAG).

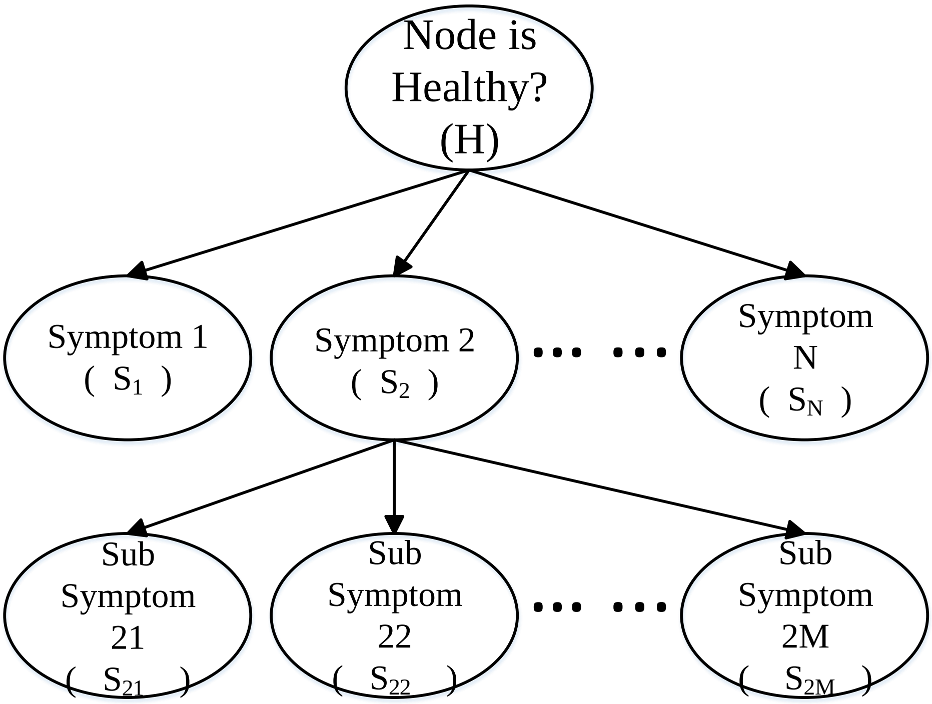

Node is Healthy? (H)
Symptom 1 (S_1)
Symptom 2 (S_2)
Symptom N (S_N)
Sub Symptom 21 (S_{21})
Sub Symptom 22 (S_{22})
Sub Symptom 2M (S_{2M})

Fig. 4.3 General Bayesian network structure

Our Bayesian network serves to model a set of nodes in terms of their status (comprised or not) and behaviours. It can be used to predict the most likely status of a node based on past observed behaviours.

To calculate this prediction, one method is the maximum likelihood approach. It is the learning process of Bayesian network from collected data. These data can be used to estimating parameters of a Bayesian network, that denote the nodes status. Note that the data sets could be either complete or incomplete, especially from a real network we usually get incomplete ones. This approach is based on the likelihood principle, that prefers the predictions (or estimates) with maximal likelihood (in other words, it favours the predictions can maximize the probability of observing the collected data sets) [25].

There are alternatives of learning process, such as Bayesian approach and constraint-based approach. They can still do the job but either requires more input or has some extra constraints [25].

A general Bayesian network structure employed in our case is shown in Figure 4.3. To determine whether a node is safe (not compromised, denoted by H), we need to

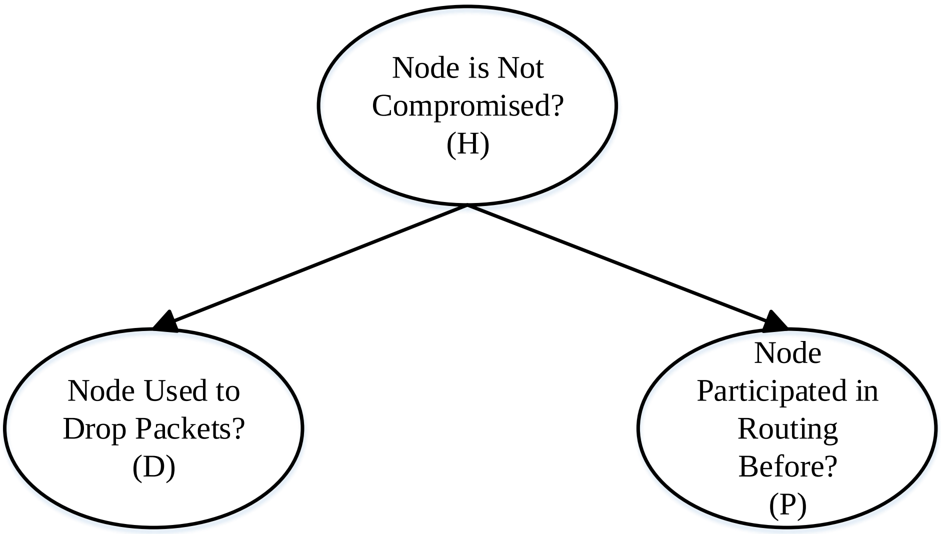

Node is Not Compromised? (H)
Node Used to Drop Packets? (D)
Node Participated in Routing Before? (P)

Fig. 4.4 A Bayesian network example

observe the node's symptoms; some symptoms may require further observation of their sub-symptoms.

Consider a basic practical example shown in Figure 4.4. The purpose is to determine a node's "health" status (node is compromised or not), denoted by variable H. Two symptoms are considered: the first is "node used to drop packets" (denoted by variable D). Note that it is normal for a node to drop a packet sometimes for a valid reason, e.g. bad link quality, but the term "drop packet" here implies that the number of dropped packets is unusually large. Also, "node participated in routing before or not" (denoted by variable P), can help to identify attacks including selective forwarding, sink hole, black and grey hole. These variables are binary, represented by T (true) or F (false) for variable H, D and P. Nodes in this DAG represent the aforementioned propositional variables. Edges in the graph represent "direct causal influences" among these variables, e.g. the node participated in routing before (P) is a direct cause of node not being compromised (H). All these causal influences are presented by conditional probabilities, an example shown in the last two sub-tables of Table 4.2 (which is also an example of initial estimates to be explained later). Given this causal structure, one would expect the dynamics of changing belief to satisfy some properties. For example, if we get a record that the sensor node dropped a packet, our belief that the node participated in routing before would probably decrease.

Table 4.1 Incomplete data sets $\mathscr{D}$

$\mathscr{D}$	H	D	P
observation$_1$	?	*F*	*T*
observation$_2$	?	*T*	*F*
observation$_3$	?	*T*	*T*

In practical cases, the recorded node symptoms (referred to as data sets) may be incomplete due to some reason, e.g. a node being compromised or not cannot be directly observed (in fact the purpose of creating Bayesian network is to determine it). Table 4.1 shows an example of incomplete data sets $\mathscr{D}$ with 3 different recorded data cases: **observation**$_1$, **observation**$_2$ and **observation**$_3$. A data case is a record of a set of symptoms shown by a node, in other word, a record with certain combination of instantiation (h, d, p), in which the status parameters $(h,d,p) = (T,T,T)$ denote that this node has not been compromised, used to drop packet and participated in routing before, respectively, and $(h,d,p) = (F,F,F)$ denote that this node has been compromised, not used to drop packet and not participated in routing before, respectively. The symbol "?" represents the missing values of variables.

The goal is to calculate the expected empirical distribution of nodes status H based on the incomplete data set. Some initial estimates are assumed as shown in Table 4.2, where $F(h=T)$ denotes the probability of a node is not compromised ($F(h=F)$ represents the probability of contrary status), and $F(d=T|h=T)$ denotes the probability of a node used to drop packet given that it is not compromised (by such analogy, the denotations of all the other combinations of $F(d|h)$ and $F(p|h)$ can be obtained). The initial estimates are based on common sense: a comprised node is more likely to drop data packets and not participate in previous routing. By contrast, a healthy node (not compromised) is more likely to participate in routing, but may still drop data packets for some reason, e.g. data transmission error.

Then a local search method, called expectation maximization (EM), is employed. That is, we first completes the data set (we have only got incomplete one as shown in table 4.1 so far), inducing an empirical distribution, and then uses it to estimate parameters. To illustrate the process of completing a data set, consider again the data

Table 4.2 Initial estimates

H	$F(h)$
T	0.8
F	0.2

H	D	$F(d\|h)$
T	T	0.1
T	F	0.9
F	T	0.8
F	F	0.2

H	P	$F(p\|h)$
T	T	0.5
T	F	0.5
F	T	0.25
F	F	0.75

Table 4.3 Completed data sets

H	D	P	$F_{\mathscr{D}}(.)$
T	T	T	To be determined
T	T	F	To be determined
T	F	T	To be determined
T	F	F	To be determined
F	T	T	To be determined
F	T	F	To be determined
F	F	T	To be determined
F	F	F	To be determined

set in table 4.1. The first case in this data set has one variable with missing value, H. Hence, there are two possible completions for this case. Although we do not know which one of these completions is the correct one, we can compute the probability of each completion based on the initial set of parameters we have.

The probability of an instantiation, say, $(h,d,p) = (T,F,T)$ (denotes node is not compromised, node did not use to drop packet and node participated in routing before), is computed by considering all its occurrences in the completed data set (as shown in table 4.3, the occurrence probabilities of each instantiation are to be calculated later in this section), by adding up the probabilities of seeing them in the completed data set. There is one occurrence of the instantiation $(h,d,p) = (T,F,T)$ in the competed data set, which result from completing the **observation**$_1$. Thus, the probability of seeing the completion is given in the coming paragraphs.

The occurrence probability of an instantiation $(h,d,p) = (T,F,T)$ according to (4.10) is given by

$$
\begin{aligned}
& F_{\mathscr{D}}\left(h=T, d=F, p=T\right) \\
& =\frac{F\left(h=T|\mathbf{observation}_1\right)+F\left(h=T|\mathbf{observation}_2\right)+F\left(h=T|\mathbf{observation}_3\right)}{3} \\
& =\frac{F\left(h=T|\mathbf{observation}_1\right)}{3}
\end{aligned}
\tag{4.8}
$$

note that both $\mathbf{observation}_2$ and $\mathbf{observation}_3$ do not contain $d=F$ and $p=T$ at the same time, thus $F\left(h=T|\mathbf{observation}_2\right)$ and $F\left(h=T|\mathbf{observation}_3\right)$ are 0 and do not appear in the later part of calculation for $F\left(h=T, d=F, p=T\right)$. And then we have

$$
\begin{aligned}
& F_{\mathscr{D}}\left(h=T, d=F, p=T\right) \\
& =\frac{F\left(h=T|\mathbf{observation}_1\right)}{3} \\
& =\frac{F(h=T|d=F,p=T)}{3}=\frac{F(d=F,p=T|h=T)F(h=T)/F(d=F,p=T)}{3} \\
& =\frac{\frac{F(d=F|h=T)F(p=T|h=T)F(h=T)}{F(h=T)F(d=F|h=T)F(p=T|h=T)+F(h=F)F(d=F|h=F)F(p=T|h=F)}}{3} \\
& =\frac{0.9\times 0.5\times 0.8\div(0.8\times 0.9\times 0.5+0.2\times 0.2\times 0.25)}{3}\approx 0.324
\end{aligned}
\tag{4.9}
$$

In general sense, the expected empirical distribution derived the incomplete data set $\mathscr{D}$ is defined as:

$$
F_{\mathscr{D}}\left(\alpha_e\right)\overset{\text{def}}{=}\frac{1}{N_{ds}}\sum_{\mathbf{observation}_i,\mathbf{c}_i|=\alpha_e} F\left(\mathbf{c}_i|\mathbf{observation}_i\right), \tag{4.10}
$$

where α_e is an event with certain combination of instantiation (h,d,p), N_{ds} is the size of the incomplete data sets, and $\mathbf{c}_i$ are variables with unrecorded values of case $\mathbf{observation}_i$. Note that $\mathbf{observation}_i, \mathbf{c}_i| = \alpha_e$ means that event α_e is satisfied by complete case $\mathbf{observation}_i, \mathbf{c}_i$, hence we are summing $F\left(\mathbf{c}_i|\mathbf{observation}_i\right)$ for all cases $\mathbf{observation}_i$ that satisfy event α_e.

Repeating this process can obtain the probability of all the other instantiations $F_{\mathscr{D}}(h,d,p)$, which can be used to complete the table 4.3 by replacing all the unknown value.

Then the EM estimate of a node not been compromised based on incomplete data sets $\mathscr{D}$ is written as

$$F_{\mathscr{D}}(h=T)=\sum_{d,p}F(h=T,d,p) \tag{4.11}$$

where d and p denote all possible values of d and p, respectively. Other parameters such as $F_{\mathscr{D}}(d|h)$ and $F_{\mathscr{D}}(p|h)$ can be calculated by

$$F_{\mathscr{D}}(d|h)=\frac{F_{\mathscr{D}}(h,d)}{F_{\mathscr{D}}(h)} \tag{4.12}$$

$$F_{\mathscr{D}}(p|h)=\frac{F_{\mathscr{D}}(h,p)}{F_{\mathscr{D}}(h)} \tag{4.13}$$

for example, $F_{\mathscr{D}}(p=T|h=F)$ can be calculated as

$$F_{\mathscr{D}}(p=T|h=T)=\frac{F_{\mathscr{D}}(h=T,p=T)}{F_{\mathscr{D}}(h=T)}=\frac{\sum_d F_{\mathscr{D}}(h=T,d,p=T)}{F_{\mathscr{D}}(h=T)} \tag{4.14}$$

Repeating this process, all the other $F_{\mathscr{D}}(d|h)$ and $F_{\mathscr{D}}(p|h)$ can be obtained.

All the results derived from (4.10), (4.12) and (4.13) based on incomplete data sets $\mathscr{D}$ constitute the $\mathscr{D}$ estimates that serves as the replacement of initial estimates shown in Table 4.2. If we continue to observe the network and fetch new incomplete data sets $\mathscr{D}_1$, $\mathscr{D}_2$ ... $\mathscr{D}_m$ where m is a positive integer, as proved in Chapter 17 of [25], for any m, $\mathscr{D}_{m+1}$ estimates have a higher likelihood than that of $\mathscr{D}_m$ estimates. Thus all the above procedures can be repeated to update the $\mathscr{D}$ estimates to $\mathscr{D}_1$ estimates, $\mathscr{D}_2$ estimates, and so on, in order to get estimates with higher likelihood.

A potential problem of the aforementioned Bayesian network based risk determination method is that a certain suspicious node's (or "target node") behaviours need to be monitored by its neighbouring nodes (so called "watcher") while these nodes themselves might be malicious. Whether these "watchers" are reporting honestly becomes a new issue. How to acquire correct behaviour information of the target node under the existence of some dishonest "watchers" is considered as a classical agreement problem called Byzantine Generals' Problem. If l_d is the number of dishonest watchers involved in the monitoring process, it has been proved that we can still obtain the correct information of target node if the total number of "watchers" n_t satisfies $n_t \geq 3l_d + 1$ [58]. Applying this property to our case, assume the entire WSN network has nodes deployment density of ρ_d nodes per square meter, the malicious fraction of the network is v_m, size of neighbouring area of target node is A_t square meter, it can be concluded that the accurate status of a target node can be obtained if the number of watchers n involved in monitoring the target node satisfies

$$n_t \geq 3v_m\rho_d A_t + 1 \tag{4.15}$$

where n_t is clearly an integer.

4.3.4 Route Discovery in ETARP

The ETARP utilizes the advantages of original AODV together with the novel adoption of utilities and Bayesian network. All these features are achieved by making full use of the existing mechanism of AODV without extra complexity and routing overhead.

As ETARP is in operation, every node keeps monitoring its neighbouring nodes' behaviour, and calculate their trustworthiness (which is denoted by H discussed in Section 4.3.3) by constructing a Bayesian network (details have been addressed in Section 4.3.3). Afterwards, the expected utility of a single hop transmission from any node to one of its neighbouring nodes can be determined, according to the method addressed in Section 4.3.2.

Suppose that a process at source node wants to send a packet to destination node, the ETARP algorithm maintains an "inverse expected utility count" table at each node in the network, keyed by destination, giving information about that destination, including the neighbour to which to send packets to reach the destination. First, source node looks in its table. If the source node does not find an entry for destination, it has to discover a route to destination node. To locate destination node, the source constructs a RREQ packet and broadcasts it using flooding. The rest of the process is very similar to that discussed in Section 3.2.3, the difference is that ETARP requires changes in the format of control messages described earlier in Section 4.3.1. For instance, the “hop count” field in RREQ message is replaced with “inverse expected utility count” which here means the product of inverse expected utilities of all hops along the route from the originator node to the node handling the request. Similarly for the RREP message, the field “hop count” is replaced with “inverse expected utility count” which refers to the product of inverse expected utilities of all hops along the route from the originator node to the destination node.

At the end of the discovery process, a new route with the minimum “inverse expected utility count” (equivalent to maximum expected utility) that can reach destination node, is created. Therefore, unlike the original AODV and AODV-EHA described in Chapter 3, the proposed ETARP intends to find out the route with maximum expected utility (a measure balances energy efficiency and security concern) rather than least hops or least expected transmission cost. The practical operation of ETARP is similar to original AODV and AODV-EHA except for small changes are in the formation of the corresponding messages: RREQs, RREPs, etc. Since the original AODV and AODV-EHA routing protocol send these messages (RREQ, RREP, etc.) in the route discovery process, there is no additional routing overhead in ETARP.

4.4 Performance Evaluation

In this chapter, the safety performance and energy efficiency performance of the ETARP routing protocol are analysed. Two competitors are chosen for comparison. The first protocol is LTB-AODV, which is dedicated to the mitigation of network attacks based on the observed past behaviours of nodes [66]. The other protocol for comparison is AODV-EHA which is an energy efficient protocol aware of energy harvesting [31]. Note that as summarized in Section 2.5, even though there are a few routing protocols that consider security and energy efficiency at the same time, but they have additional constraints. For example, some require extra information such as nodes location, some others depend on cryptographic authentication. Since the conditions are different, those candidates are not suitable to serve as competitors.

In performance evaluation, “safety performance” involves the average number of compromised nodes that are likely to be encountered in a single transmission given a specific malicious ratio (fraction of nodes that are malicious). It can be called risk level as well, the less the better. Likewise “energy efficiency performance” here involves the estimated energy cost after successfully delivering a data packet in a single transmission along the route discovered by a specific routing protocol, the less the better as well.

4.4.1 Existing Protocols for Comparison

Overview of LTB-AODV to compare safety

In LTB-AODV [66], different “trust values” are computed for all the routes to represent the risk level, then the algorithm chooses the route with the least hops among the candidates having a trust value higher than a given threshold. Let $T_l^R(n)$ denote the level of trust of any specified node n on any chosen neighbour node n. It is calculated as:

$$T_l^R(n) = \frac{\text{Number of packets forwarded by n}}{\text{Number of packets to be forwarded by n}} \tag{4.16}$$

The values of the numerator and denominator are obtained by node l monitoring the traffic of its neighbour n.

For a complete route, the total trust value, denoted by T_{route}^R, is given as

$$T_{route}^R = \prod_m T_m^R \tag{4.17}$$

where T_m^R is the trust value of the m-th node on its next hop. LTB-AODV is a modification of the AODV protocol incorporating the above trust estimation technique. Thus, LTB-AODV chooses the most trusted route.

Table 4.4 Simulation parameters

Parameters	Descriptions
Simulation Area	500 m × 500 m
Node Radio Range	250 m
Traffic Type	CBR
Packet Size	127 bytes
Data Rate	20 kbps
Signal to Noise Ratio (SNR) Threshold β	10
Processing Power Level P_c	10^{-4} W
Receiving Power Level P_r	5×10^{-5} W
Outage Requirement $\mathscr{P}_{out}^{*}(i,m)$	10^{-4}

Overview of AODV-EHA to compare energy efficiency

In AODV-EHA [31], the predictions of data transmission cost (in terms of energy) are computed for all the routes while considering the energy harvesting technology. The algorithm chooses the route with the least energy cost approximation for data transmission. For any specific route, let E_m denotes the estimation of energy cost after successfully deliver a data packet from the m-th node to its next hop, then for the whole route, the total energy cost, denoted by E_{route} is given as

$$E_{route} = \sum_{m} E_m \tag{4.18}$$

AODV-EHA is a modification of the AODV protocol incorporating the above energy cost estimation. Thus, AODV-EHA chooses the most energy efficient route with minimum E_{route}.

4.4.2 Simulation Setup

The experimental evaluation is carried out by means of MATLAB simulations using the Monte-Carlo method. The two criteria considered are safety performance and energy efficiency performance. The number of nodes in the simulated area varies from 50 to 90, and for each nodes number, 300000 simulation runs are carried out.

The size of the simulated area is 500 $m \times 500$ m. The communication range of each node is 250 m. Considering the WSN applications this chapter focus on, IEEE 802.15.4

is chosen for the physical and data link layer, which is suitable for low data rate but very long battery life applications [39]. According to the specification mentioned in [39], the traffic type is CBR with a data rate of 20 Kbps, and the size of each packet is 127 bytes. Since the transmission cost prediction partly depends on previous works [95], therefore for those parameters required for the prediction process we continue to use the same values as adopted in [95]. Details are listed in Table 4.4.

Every simulation contains a certain malicious fraction of the network. These compromised nodes are located randomly in the simulation area, and they are assigned with certain behaviours that can further affect the route discovery process.

4.4.3 Experimental Results

The chosen scenario is analogous to the application of enemy detection on the battlefield. The data collection device (possibly a human) could be assigned to any position in the area where the WSN is deployed, rather than being tied to a fixed place.

A large network can be considered as an interconnection of many smaller ones. We believe that the current results can be generalized to larger networks for the following reasons. Suppose we are trying to find an optimal route from a specific source to a specific destination in a large network. The whole optimal route could be further decomposed to multiple sub-routes, each one traverses a smaller sub-network. Since these sub-networks are part of the whole network, they will keep some identical properties, e.g. nodes density, malicious rate, and so on. Therefore, for the same routing protocol, the sub-route of the whole optimal route also serves as the optimal route in the corresponding sub-network.

In other words, for the same routing protocol, its routing process in the whole network is equivalent to the repeat of routing process in multiple sub-networks, and this protocol won’t show a different and surprising behaviour in a large network compared to the behaviour of smaller ones.

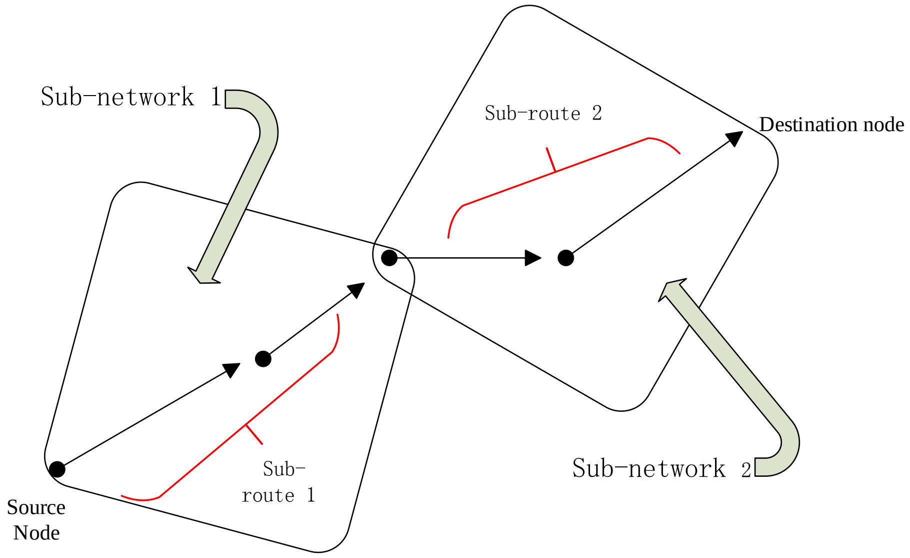


Fig. 4.5 Example of network decomposition

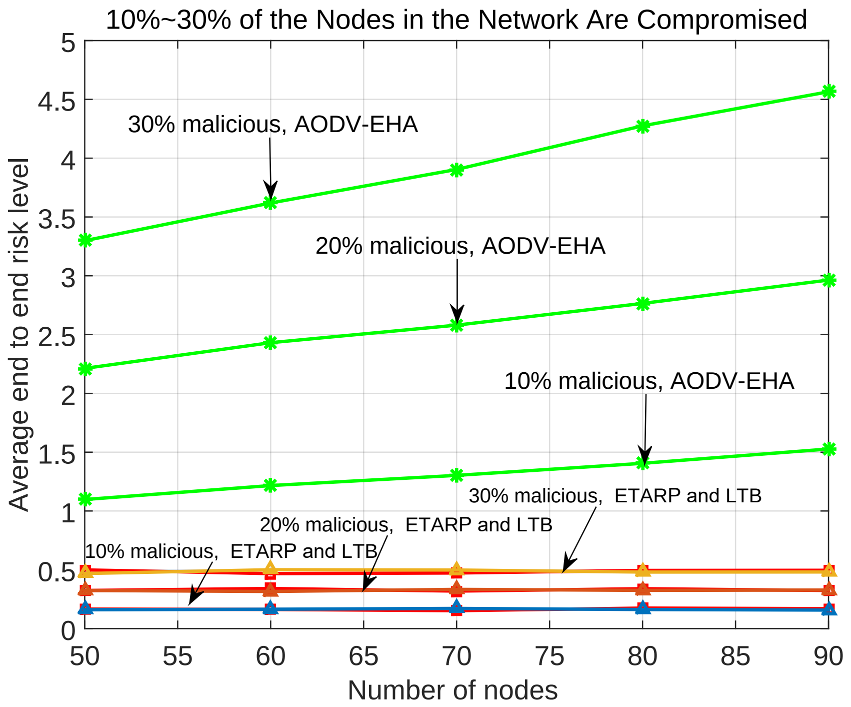


Fig. 4.6 Average route risk level (average number of compromised nodes encountered on the route)

Figure 4.5 shows a simple example of the aforementioned network decomposition, the whole optimal route is divided into 2 sub-routes and transverses 2 sub-networks. The number of sub-routes and sub-networks could be extended to any volume.

Safety Performance

Figure 4.6 shows the safety performance of the 3 protocols under different compromised ratios (10% – 30%).

Remark. *The number of compromised node in the network is closely related to the attacker's subjective intention of paralysing the network, and in some sense it is unpredictable. The authors in [5] figure out that, for an unspecific (unknown) type of attack against WSNs, if no more than 20% of the nodes are malicious, the attack can be detected and confined, which is due to the fact that the great majority of nodes are still behaving properly and it is not complicated to distinguish the misbehaving ones. In some other research studying security of WSNs, the numbers of malicious nodes in their simulations are usually assumed to be 1% – 30% of the total number of sensor nodes in the network [30, 43, 60].*

The upper three lines, from top to bottom, denote the safety performance of AODV-EHA, with the compromised ratio from 30% down to 10%. The lower three pairs of inter-weaved lines, from top to bottom, represent the safety performance of ETARP and LTB-AODV, at the compromised ratio from 30% down to 10%. It can be seen that, as the malicious ratio increases from 10 % to 30 %, the difficulty of maintaining security in the network is increasing. On the other hand, under different malicious ratios, the safety performance lines of ETARP and LTB-AODV wind around each other while fluctuating a little bit as the nodes number increase. Therefore, we can conclude that ETARP can maintain a similar safety performance as LTB-AODV.

By comparison, there is a more notable increment of risk level (average number of compromised nodes expected to encountered on the route) for AODV-EHA, as the malicious ratio increases in the network. Under any certain malicious ratio, the risk level line for AODV-EHA keeps increasing with the number of nodes in the network. This is due to the fact that network coverage area remaining the same while the number of compromised nodes increases. Thus, we can conclude that there is no security in AODV-EHA, as expected since its original design did not take safety into consideration.

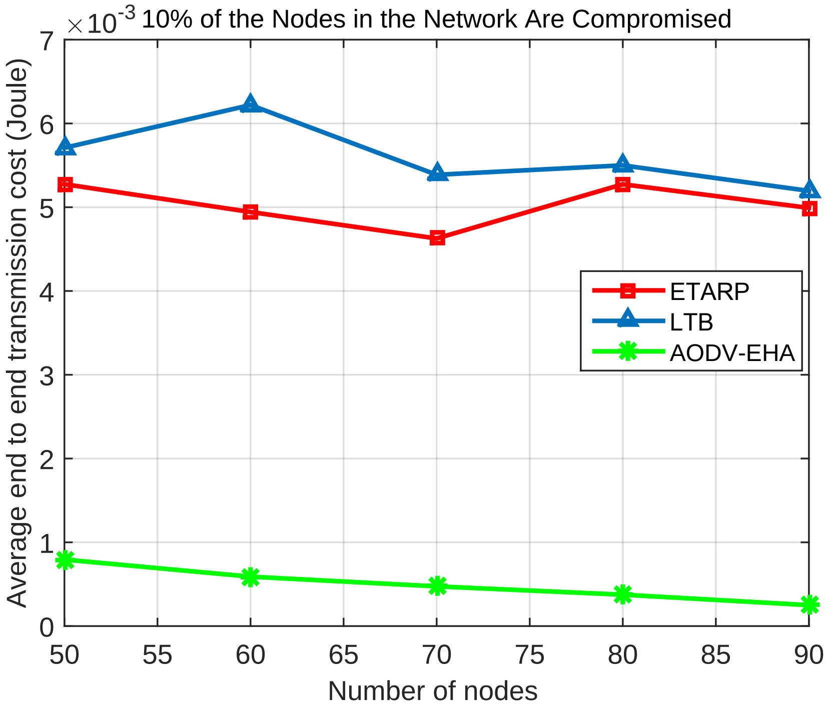


Fig. 4.7 Average end to end transmission cost (Joule)

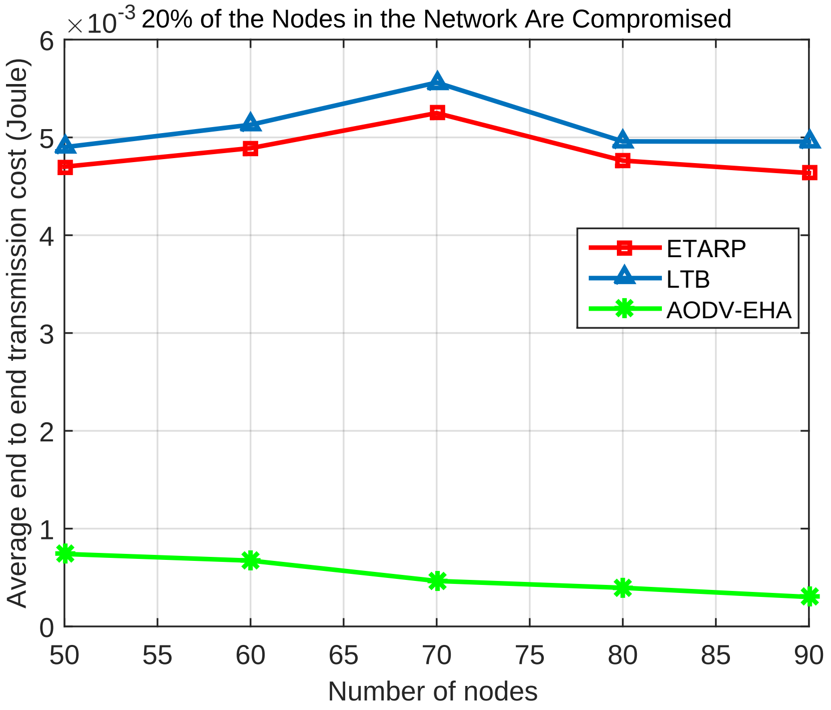


Fig. 4.8 Average end to end transmission cost (Joule)

Energy Efficiency Performance

Figure 4.7 – 4.9 show the average energy cost of each transmission under different compromised ratios (10% – 30%).

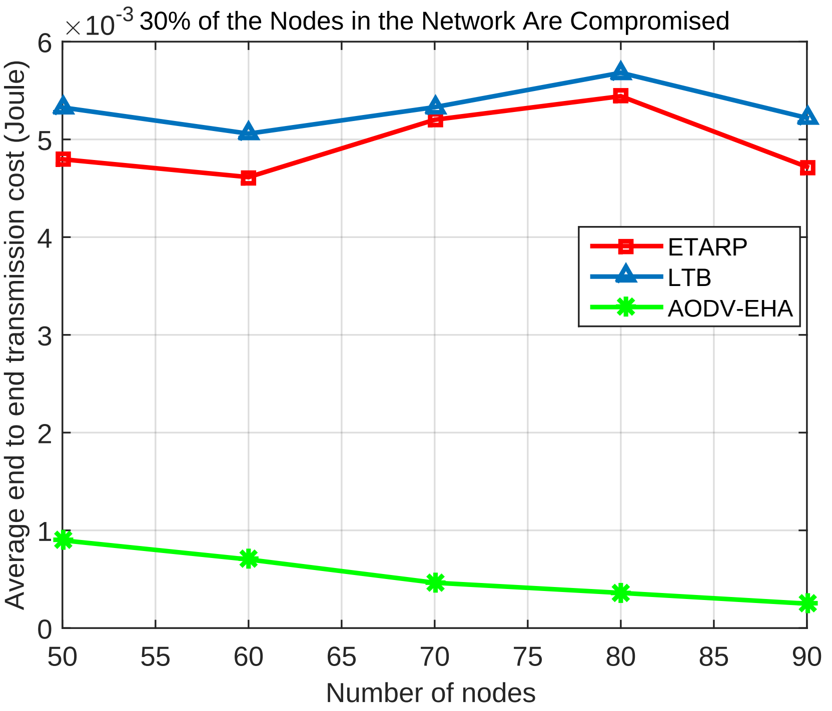


Fig. 4.9 Average end to end transmission cost (Joule)

For any certain malicious ratio, both lines of ETARP and LTB-AODV fluctuate per number of nodes in the network. ETARP consistently uses less average transmission cost compared to LTB-AODV in terms of energy. More specifically, the energy cost of ETARP is reduced by 2.4% to 20.5% in comparison to that of LTB-AODV, depending on various situations. But there is no clear increase or decrease tendency of the energy cost as the nodes number ascends. In honest scenarios, usually the average transmission cost is inverse proportional to nodes number. It is because the increment of nodes density provides more choices of nodes, and is more likely to find a more energy efficient route. But in our case, as the malicious ratio is constant, more nodes means not only more potential routes, but also more compromised nodes existing in the network. Since route discovery tries to avoid comprising malicious node, therefore the energy efficiency, to some extent, is sacrificed sometimes.

By comparison, the average transmission cost of AODV-EHA under any certain malicious ratio tends to decrease as the nodes number increase. The cost appears to be less than that of ETARP or LTB-AODV, but as illustrated in Section 4.4.3, the route determined by AODV-EHA is likely to be a dead link almost in every transmission.

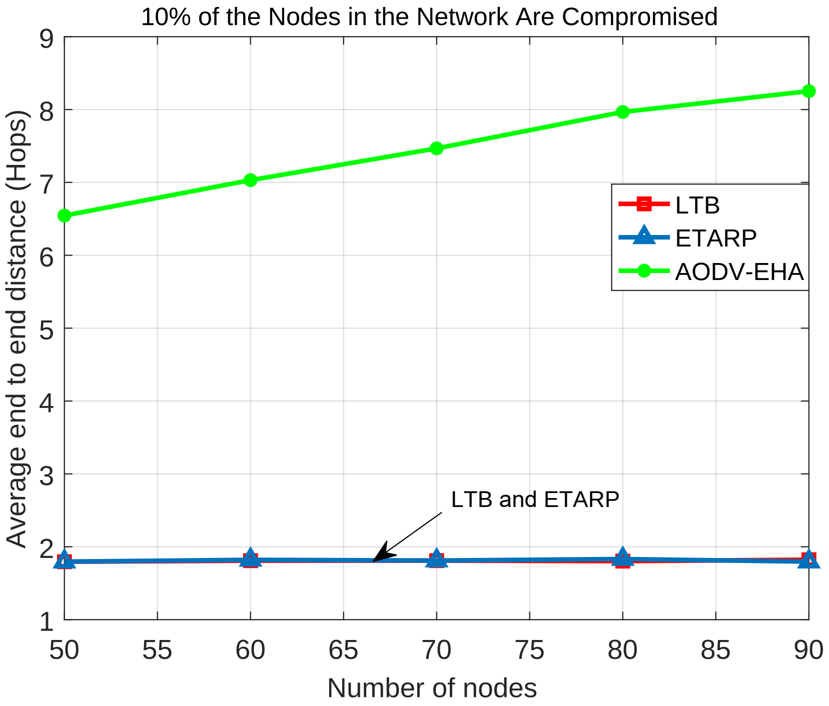


Fig. 4.10 Average route length (hops) versus the number of nodes

A dead link makes the theoretical minimum energy cost of AODV-EHA meaningless, since the packets are probably dropped on their way without reaching the destination. All the energy already spent on the transmissions are wasted, even though it is ostensibly less than that of ETARP.

Average Route Length

Under AODV-EHA, the route length is increasingly high as the number of nodes in the area goes up (it is because the increment of nodes density provides more choices of nodes, and is more likely to find a more energy efficient route at the price of longer route length), while that of LTB-AODV and ETARP are relatively stable, as can be seen from Figure 4.10 – 4.12. It can also be seen that regardless of compromised ratios, there is no clear difference in route length between LTB-AODV and ETARP as the nodes number ascends. This is because both LTB-AODV and ETARP are designed to be secure, they try not to involve any compromised node in route discovery. In addition, ETARP does not pay any special attention on minimizing route length. Therefore, under any certain

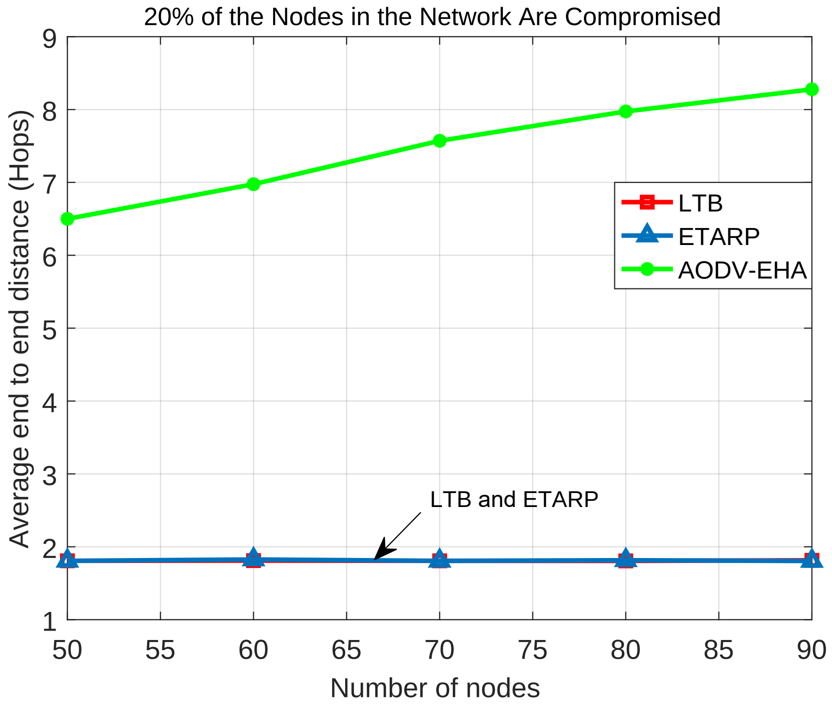


Fig. 4.11 Average route length (hops) versus the number of nodes

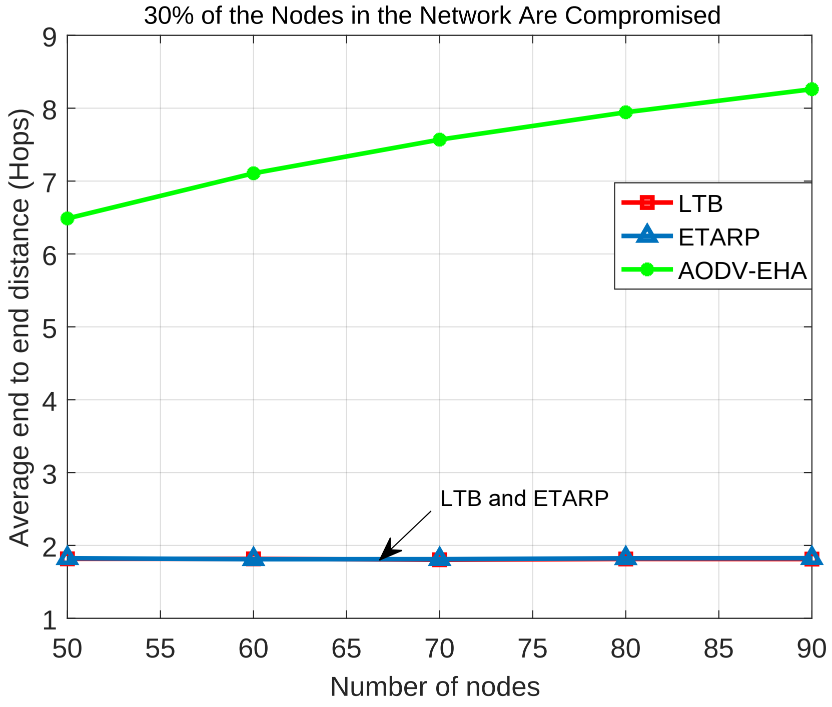


Fig. 4.12 Average route length (hops) versus the number of nodes

compromised ratio, ETARP does not have any advantage in terms of end-to-end delay (denoted by route length) over LTB-AODV.

From all the above results gained about different performances, we can conclude that under different compromised ratios, ETARP has advantages in terms of energy efficiency in transmission while it can still maintain almost the same safety performance as LTB-AODV at the same time (stated in Section 4.4.3). But ETARP has no clear advantage over LTB-AODV in terms of end-to-end delay. By comparison, even though AODV-EHA achieves the theoretical “lowest” transmission cost, there is no security in AODV-EHA since its original design focused on reducing energy cost but did not give attention to security.

4.5 Summary

In this chapter, we proposed the ETARP routing protocol for WSN applications operating in extreme environments usually for military use, such as SDT and ASW. ETARP simultaneously considers energy efficiency and security concerns by taking advantage of utility theory. Through simulations, we evaluated the energy efficiency performance and safety performance of ETARP in comparison to LTB-AODV and AODV-EHA. Results show that although AODV-EHA has the theoretical “lowest” transmission cost, there is no security in it, while ETARP has the advantages in terms of energy efficiency in transmission while it can still maintain about the same safety performance as LTB-AODV.

Chapter 5

Vampire Attacks Detection and Defence

5.1 Introduction

In this chapter, RCPED protocol, is proposed to protect routing protocols from Vampire attacks that have been introduced in Chapter 1. Compare to the existing solutions, our approach is independent of cryptographic methods, which can avoid extra computation cost, transmission cost and even hardware (used for encryption purpose). These advantages are quite meaningful as the wireless sensors are with limited size, computing capability and battery.

The nominated scenario in this chapter can be considered as the application of environment surveillance. The engineer just stays at a fixed observation point (location is decided by the engineer) in the region covered by the deployed WSN, and collects data from the nodes.

In Section 5.2 and Section 5.3, a procedure for detection of Vampire attacks is described in detail. Section 5.4 discusses how to mitigate the harm from Vampire attacks. Performance evaluation of the proposed solution in terms of simulation results is presented in Section 5.5.

5.2 General Concept and Passive Detection

The general approach of RCPED against Vampire attacks is illustrated in Figure 5.1. It consists of passive detection (further addressed in Section 5.2.1 and Section 5.2.2), and active detection (further addressed in Section 5.3).

The proposed solution in this chapter is designed to reduce the cost (e.g. energy), it would be resource consuming if initiating the active detection on malicious nodes directly. Therefore we only let passive detection with less cost of resource in operation at the very beginning. Passive detection is integrated in the normal routing process and continually monitors the network, with no significant additional actions. Similar to any on-demand solution, active detection remains silence until any suspicious sign is captured by passive detection. If active detection is triggered, it tries to identify which nodes are possibly participating in any Vampire attacks. Nodes in the network are alerted afterwards, to stop suspicious nodes from involving in the route discovery of any future data transmission.

Previous work in [31] shows that the approximate cost of transmitting a data packet from an arbitrary node in the network to a stationary observation point (denoted by $E(M)$) has a functional relationship with the number of nodes in the network (denoted by M). If the relationship between the transmission cost and density of nodes in the network can be determined, the expected average transmission cost corresponding to a specific nodes density in the "normal case" (when no attacks against the network are happening) can be figured out as well.

Provided that the task described above is done, we can track the data transmissions in the network and calculate the energy cost of incoming packets at the observation point. If the average of these recorded costs is significantly higher than the expected value for the "normal case", then an attack may be suspected. This process is called passive detection because it involves measurements that do not interfere with the normal operation of the network. Passive detection is a type of anomaly detection [14] which refers to the process of looking for abnormal behaviour (in this case, behaviour of the

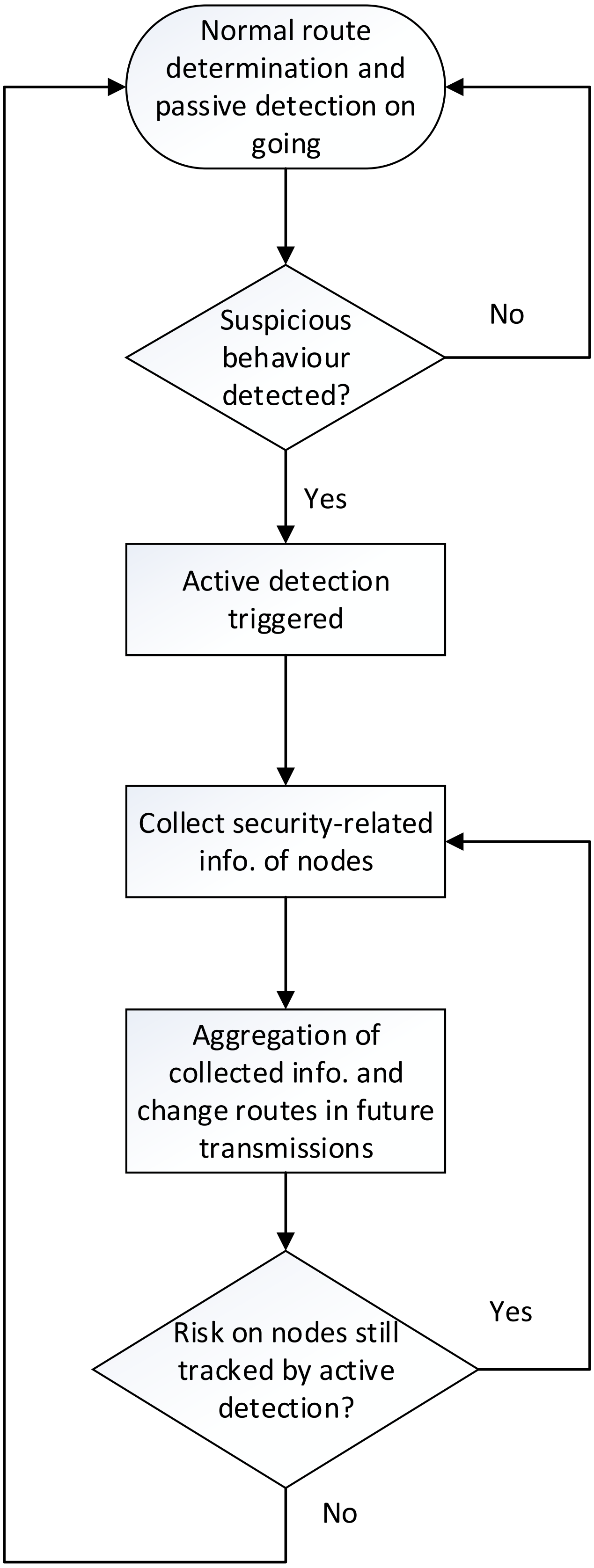

Normal route determination and passive detection on going
Suspicious behaviour detected?
No
Yes
Active detection triggered
Collect security-related info. of nodes
Aggregation of collected info. and change routes in future transmissions
Risk on nodes still tracked by active detection?
Yes
No

Fig. 5.1 General concept of detection and protection against of Vampire attacks

sensors). Two subsequent problems need to be clarified: (1) the definition of normal (2) the definition of significant deviation. These are addressed later in Section 5.2.1.

5.2.1 Defining Normal Case and Significant Deviation

Regression analysis is a well known technique in statistics [17, 26]. It is a classic approach to determine the relationship between $E(M)$ and M.

According to the data and experimental results in Chapter 3, a non-linear exponential function is likely to describe the relationship between $E(M)$ and M, and specifically:

$$E(M) = a_l e^{b_l M} \cdot \varepsilon, \quad \ln \varepsilon \sim N\left(0, \sigma^2\right) \tag{5.1}$$

where e is the base of the natural logarithm, a_l, b_l and σ are constant parameters that are independent of M.

According to Friis transmission equation [88], the energy consumption over a source node-destination node distance is proportional to the square of that distance. If one or more relay nodes could be found in between the source node and destination node, the energy consumption could be significantly reduced. A larger M leads to increment of nodes density and can provide more choices of nodes, therefore it is more likely to find a more energy efficient route that consists of more nodes (more hops). But the adoption of these extra nodes needs extra energy to maintain the operation of themselves, which partially offsets the saved energy. This is why $E(M)$ in Equation (5.1) takes the shape of an exponential function rather than a linear function.

The exponential form of Equation (5.1) suggests that taking the logarithmic can simplify the relationship. Let $\ln E(M) = E^{'}(M)$, $\ln a_l = a_l^{'}$, $b_l = b_l^{'}$, $M = M^{'}$, $\ln \varepsilon = \varepsilon^{'}$, thus Equation (5.1) can be transformed into a simple linear regression model:

$$E^{'}(M) = a_l^{'} + b_l^{'} M^{'} + \varepsilon^{'} \tag{5.2}$$

Next, estimates of a_l (or $a_l^{'}$) and b_l (or $b_l^{'}$), denoted by $\hat{a}_l$ (or $\hat{a_l^{'}}$) and $\hat{b}_l$ (or $\hat{b_l^{'}}$), can be determined by linear regression given a set of past records of M and corresponding $E(M)$. Details of how the records can be acquired are described in [31].

As addressed in [110], if Vampire attacks targeting stateless routing protocols are underway, simulation results show that on average, a randomly located attacker in a network with randomly generated topology, can increase the network energy consumption by a factor of 1.48±0.99 if the adversary performs a carousel (route loop) attack, and by a factor of 2.67±2.49 if the adversary performs stretch attack. The large standard deviation is because the length of the adversarial path length is affected by the position of the attacker in relation to the source or destination node. Higher network energy usage increment leads to higher possibility of Vampire attacks in operation. In worst case this number may go up to a factor of 3.96 by carousel attack, or up to 10.5 by stretch attack.

Therefore we can keep checking the expected transmission cost of any incoming packet, if there is any unnormal increment as discussed in the previous paragraph, the network is potentially experiencing a Vampire attack. Then the active detection phase is triggered, details is addressed later in Section 5.3 and Section 5.4.

All incoming data packets can carry information about their travelled route by carrying a list of encountered nodes together with their location information (nodes localisation is discussed in Section 5.2.2), these routes information are essential for the calculation of expected transmission cost of packet delivery mentioned in the previous paragraph (estimation details are given in Section 5.2.2). Note that the transmission of these location information can cost a bit more than that of standard packet, this need to be taken into consideration in later evaluation. According to the NMEA-0183V20 standards [75] formulated by the National Marine Electronics Association of USA, a typical GPS positioning information accounts for 88 byte, but most of the information (such as velocity and magnetic declination) can be consider as redundant in our application, only the coordinates information are retained.

5.2.2 Practical Issues in Passive Detection

As discussed in Section 5.2.1, in passive detection, expected transmission cost of incoming packets need to be determined. Furthermore, the determination process needs locations of nodes on the route that those packets travelled through. Details on how to solve these practical issues are given in this section.

Estimation of Transmission Cost on a Specific Route

On any chosen route i spanning a total number of J_i nodes, the expected total transmission cost $E(i)$ in terms of energy can be calculated as [31]:

$$E(i) = E(i,1) + E(i,2) + ... + E(i,J_i - 1) \tag{5.3}$$

where $E(i,m)$ is the estimated transmission cost from the m-th node on this route to its next hop ($1 \leq m \leq J_i - 1$). More details of the above calculations can be found in Section 3.2.3.

Node Localisation

GPS is the most obvious means to establish the locations of nodes. In order to reduce overhead, most localization systems use one or more anchor nodes equipped with GPS chip instead of including GPS in every node [52]. These anchor nodes broadcast their current positions periodically to sensor nodes to estimate their locations.

For the long-term monitoring application under consideration, since nodes in the network usually unreachable after deployment, battery life is the major constraint. A high updating frequency such as one sample per second is meaningless when monitoring weekly or even monthly. A push-to-fix mode has been suggested for long-term operating applications [89] which means the GPS is put to sleep most of time and position is only updated at regular time intervals (every 2 hours or even longer). This mode can be useful for GPS embedded nodes. For our application, nodes rarely change their positions therefore a longer time interval, e.g. one sample per day, is sufficient. Since

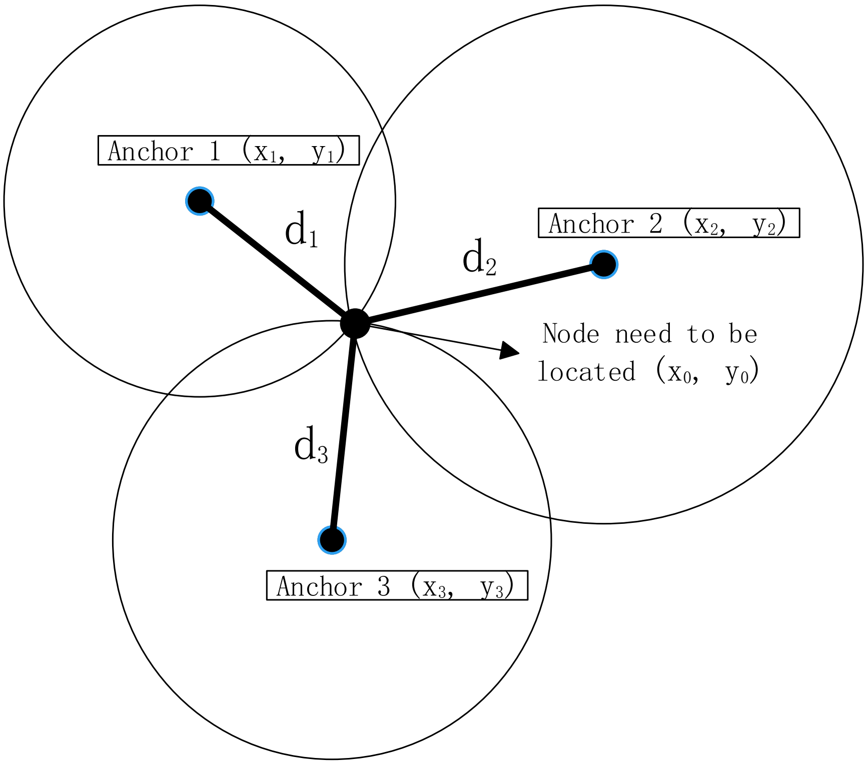


Fig. 5.2 Process of trilateration

each position updating process can last for up to 30 seconds, the energy cost of a GPS embedded node could be limited to 31.08 Joule per day [89]. If we choose a common and cheap 18650-size cylindrical lithium-ion battery cell [38] (3.3v, 1.6-Ah), the GPS embedded node can operate for more than one and a half years.

According to [44], trilateration approach shown in Figure 5.2 based on the received signal strength is the most suitable for node localisation in WSNs due to its implementation simplicity and low hardware requirement. The basic idea is as follows: the anchor nodes periodically broadcast their locations, and the nodes need to be located can receive these information and estimate the distance from anchor nodes by measuring the received signal strength (RSS). Suppose the coordinates of anchor nodes 1, 2, 3 are (x_1,y_1), (x_2,y_2), (x_3,y_3), the coordinates of the node need to be located is (x_0,y_0), and the distances between three anchor nodes to the node to be located are d_1, d_2, d_3. If we choose (x_1,y_1), (x_2,y_2), (x_3,y_3) as centres and draw 3 circles with radius d_1, d_2, d_3, respectively, and these three circles are supposed to intersect at (x_0, y_0). Then (x_0, y_0) can be determined by solving the following equations:

$$\begin{cases} (x_1 - x_0)^2 + (y_1 - y_0)^2 = d_1^2 \\ (x_2 - x_0)^2 + (y_2 - y_0)^2 = d_2^2 \\ (x_3 - x_0)^2 + (y_3 - y_0)^2 = d_3^2 \end{cases} \tag{5.4}$$

5.3 Active Detection

This section elaborates on the procedure for active detection. Passive detection is useful for detecting signs of network-level misbehaviour, but the eventual purpose is to mitigate the influence from attacker. Active detection is needed to investigate suspicions through selective testing to identify with confidence which nodes might be compromised. Compare to passive detection, active detection need to carry out more analysis and calculations (more resource consuming), thus similar to any on-demand solution, it remains silence until suspicious sign is captured by passive detection.

5.3.1 Detection of Suspicious Routes

As soon as active detection is triggered in the network, route records (identities of nodes involved, e.g. nodes number) for future incoming data packets are saved in a buffer in observation points. The information is stored in a fixed sized FIFO (first-in first-out) data buffer as illustrated in Figure 5.3. The information about the first packet will be first one to be removed when the buffer is full.

Ideally, an observation point wishes to obtain transmission records from every node in the network at least once, which means all the possible routes have been tested. If the data buffer is large enough, and we can save as much records we want, eventually the record from every node can be obtained. But in reality, the storage available for data buffer is not unlimited. Given that the sufficient records are likely to be obtained, the size data buffer, preferably as small as possible. To determine the minimum buffer size,

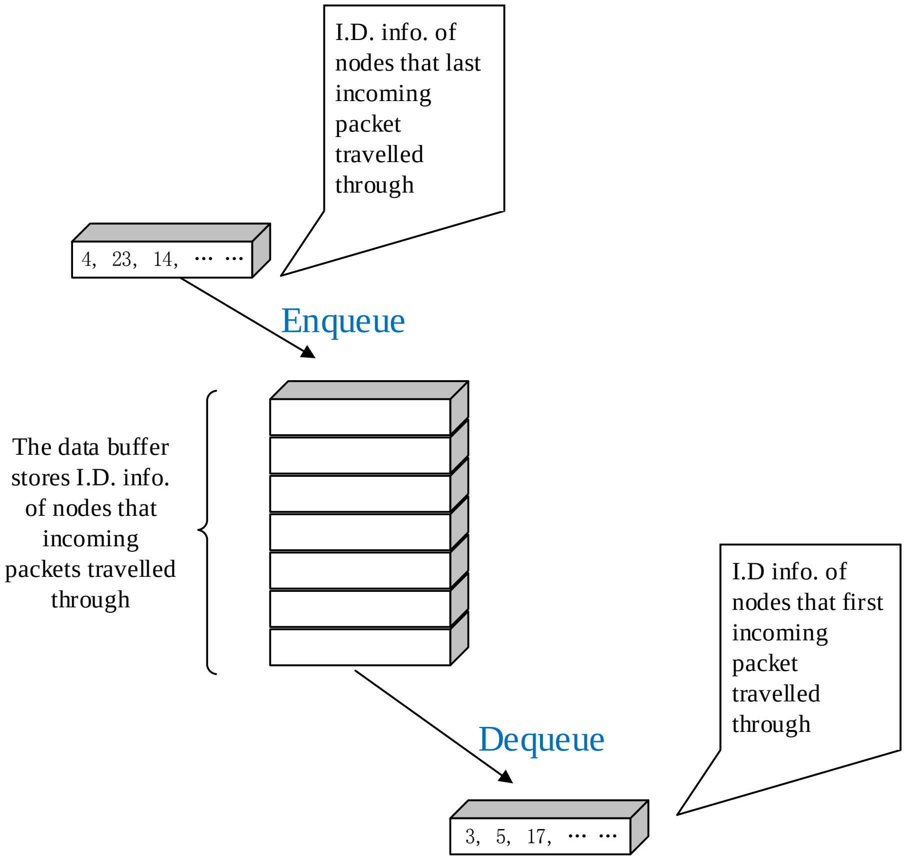

I.D. info. of nodes that last incoming packet travelled through
4, 23, 14, ⋯ ⋯
Enqueue
The data buffer stores I.D. info. of nodes that incoming packets travelled through
Dequeue
I.D info. of nodes that first incoming packet travelled through
3, 5, 17, ⋯ ⋯

Fig. 5.3 Format of data buffer

we define the event needs to be fulfilled: every node in the network has transmitted data to observation point at least once. Suppose after k_t transmissions exercised (means k_t transmission records are saved in buffer), this event is satisfied at the probability of P_e, thus the probability of its complementary event (transmission from a specific node has never been recorded) is below $(1-P_e)$:

$$\left(\frac{M-1}{M}\right)^{k_t} \leq 1-P_e \tag{5.5}$$

where M is the number of nodes in the network, $\frac{M-1}{M}$ is the probability that the transmission record of any specific node has not been obtained (assume that the probability of any node in the network communicates with observation point is equal), thus k_t has to satisfy

$$k_t \leq \frac{\log(1-P_e)}{\log\left(\frac{M-1}{M}\right)} \tag{5.6}$$

Therefore, the minimum size of the buffer is $\left\lceil \frac{\log 0.01}{\log(\frac{M-1}{M})} \right\rceil$, where $\lceil\ \rceil$ is the Ceil function. For example, if $P_e = 0.99$, nodes number $M = 50$, the minimum size of data buffer would be $\left\lceil \frac{\log 0.01}{\log(\frac{50-1}{50})} \right\rceil$ = 228.

Inspired by the route rebuilding concept discussed in [20], suppose all the information of suspicious routes that are found in buffer are denoted by $B_1, B_2, ..., B_{N_b}$, where N_b is the total number of detected suspicious routes from the buffer. Thus we can build a comprehensive vector $\mathscr{B}$ as follows:

$$\mathscr{B} = [B_1, B_2, ..., B_{N_b}] \tag{5.7}$$

we further define any specific row in $\mathscr{B}$ as $B_V = \{V_m : 1 \leq m \leq |B_V|\}$, where V_m represents each node on this route B_T, and V is an integer and $1 \leq V \leq N_b$ ($|\ \ |$ means the number of elements in set).

Note that the data buffer is not static, as transmissions going on, the data buffer is updating itself all the time. Thus $\mathscr{B}$, which is extracted form the data buffer is a “live” vector and updating itself actively as time goes by.

5.3.2 Detection of Route Loop Attackers (Carousel Attackers)

If no route loop is formulated, a specific packet is expected to travel through every node on the route only once. If a node appears multiple times in a single route B_L, a route loop is probably exists. And those nodes are marked as suspicious nodes and further investigated(details are further addressed in Section 5.4.1).

Note the mark is not constant. As mentioned in Section 5.3.1, the $\mathscr{B}$ is updating itself constantly, so the mark on a node may vary from time to time.

5.3.3 Detection of Route Stretch Attackers

If a node does not appears in a single line multiple times in $\mathscr{B}$, but more than once in multiple B_L instead, it is probably been part of formulating stretched route. It is then

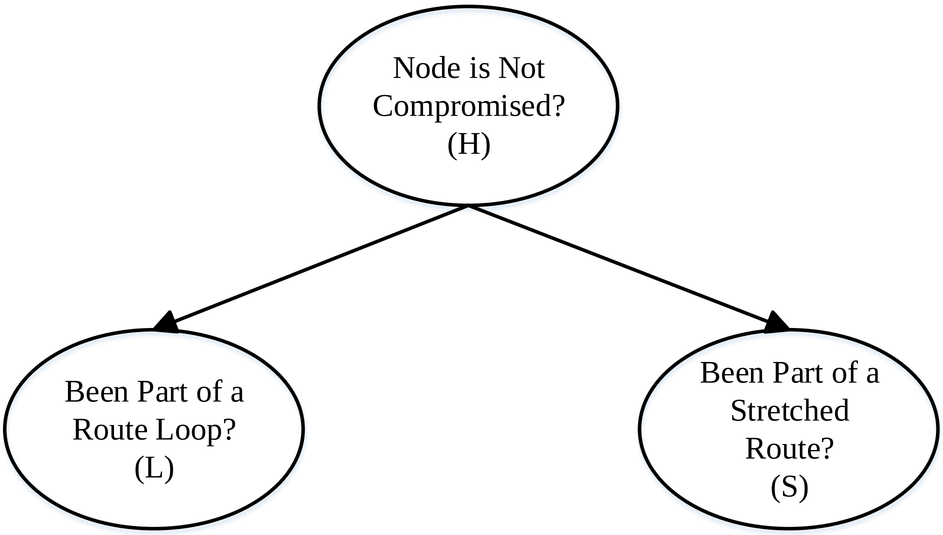

Node is Not Compromised? (H)
Been Part of a Route Loop? (L)
Been Part of a Stretched Route? (S)

Fig. 5.4 Bayesian network for information aggregation

marked as a suspicious node and further investigated (details are further addressed in Section 5.4.1).

As already been explained in Section 5.3.2, these marks are not static due to $\mathscr{B}$ is updating itself.

5.4 Protection Against Vampire Attacks in Routing

As described in Figure 5.1 of Section 5.2, the security related data obtained from Section 5.3 should be fed back to route discovery in order to mitigate the damage caused by malicious nodes.

5.4.1 Monitoring Information Aggregation

Based on the information gathered from the aforementioned detections, it is possible and necessary to calculate a “belief” about a suspicious node’s trustworthiness. Since the suspicious nodes might be part of carousel attack or stretch attack or both (more than one suspicious behaviour), here a Bayesian learning network is employed to aggregate and analyse the collected information. A general introduction of the Bayesian network and why it is employed have been given in Section 4.3.3.

Table 5.1 Incomplete data sets $\mathscr{D}$

$\mathscr{D}$	H	L	S
$\mathbf{observation}_1$	?	F	T
$\mathbf{observation}_2$	?	T	F
$\mathbf{observation}_3$	?	T	T

Table 5.2 Initial estimates

H	$F(h)$
T	0.8
F	0.2

H	L	$F(l\|h)$
T	T	0.1
T	F	0.9
F	T	0.8
F	F	0.2

H	S	$F(s\|h)$
T	T	0.1
T	F	0.9
F	T	0.9
F	F	0.1

Similar to Section 4.3.3, the practical Bayesian network employed here is shown in Figure 5.4, the purpose is to determine a node's "health" status (node is compromised or not), denoted by variable H, two symptoms are considered: "node is part of a route loop" (denoted by variable L), and "route is part of a stretched route" (denoted by variable S). These variables are binary, represented by T (true) or F (false) for variable H, L and S.

Table 5.1 shows an example of incomplete data sets $\mathscr{D}$ with 3 different recorded data cases: $\mathbf{observation}_1$, $\mathbf{observation}_2$ and $\mathbf{observation}_3$. A data case is a record of a set of symptoms shown by a node, in other word, a record with certain combination of instantiation (h, l, s), in which the symptom parameters $(h,l,s) = (T,T,T)$ denote that this node has not been compromised, used to be a part of route loop and a stretched route before, respectively. And $(h,l,s) = (F,F,F)$ denote that this node has been compromised, not used to be a part of route loop as well as stretched route before, respectively. The symbol "?" represents the missing values of variables.

The goal is to calculate the expected empirical distribution of nodes status H based on the incomplete data set. Some initial estimates are assumed as shown in Table 5.2 based on common sense; e.g. a comprised node is more likely to be part of a route loop or stretched route in previous routing.

The expected empirical distribution of the incomplete data set $\mathscr{D}$ is defined as:

$$F_{\mathscr{D}}(\alpha_t) \overset{\text{def}}{=} \frac{1}{N_{ds}} \sum_{\mathbf{observation}_i, \mathbf{c}_i = \alpha_t} F(\mathbf{c}_i | \mathbf{observation}_i) \tag{5.8}$$

where α_t is an event with certain combination of instantiation (h,l,s), N_{ds} is the size of the data set, and $\mathbf{c}_i$ are variables with unrecorded values of case $\mathbf{observation}_i$.

For example, the probability of an instantiation $(h,l,s) = (T,F,T)$ (denotes node is not compromised, node did not use to be part of route loop and node used to be part of stretched route in routing before) is given by

$$F_{\mathscr{D}}(h=T,l=F,s=T) = \frac{F(h=T|\mathbf{observation}_1)}{3} \tag{5.9}$$

Repeating this process can obtain the probability of all the other instantiations (h,l,s). Then the expectation maximization estimate of a node not been compromised is written as

$$F_{\mathscr{D}}(h=T) = \sum_{l,s} F(h=T,l,s) \tag{5.10}$$

where l and s denote all possible values of l and s, respectively. Other parameters such as $F_{\mathscr{D}}(l|h)$ and $F_{\mathscr{D}}(s|h)$ can be calculated by

$$F_{\mathscr{D}}(l|h) = \frac{F_{\mathscr{D}}(h,l)}{F_{\mathscr{D}}(h)} \tag{5.11}$$

$$F_{\mathscr{D}}(s|h) = \frac{F_{\mathscr{D}}(h,s)}{F_{\mathscr{D}}(h)} \tag{5.12}$$

All the results derived from (5.8), (5.11) and (5.12) based on incomplete data sets $\mathscr{D}$ constitute the $\mathscr{D}$ estimates that serve as the replacement of initial estimates shown in Table 5.2.

As mentioned in Section 5.3.2, the $\mathscr{B}$ is an “live” vector, therefore we can keep observing the nodes symptoms from $\mathscr{B}$ and periodically fetch new incomplete data sets $\mathscr{D}_1$, $\mathscr{D}_2$ ... $\mathscr{D}_m$ where m is a positive integer. If we keep fetching data from $\mathscr{B}$, we can get estimates with higher likelihood [25].

5.4.2 Security Information Distribution

The aforementioned security information calculated from Section 5.4.1 (which nodes are likely to be compromised, together with the probability of being compromised), need to be forwarded to the nodes in the network, for the purpose of a safer route discovery. For the sake of energy efficiency, rather than directly flooding security related information through the entire network, they are passed to certain "cluster heads" first, and then broadcast to surrounding nodes [120]. Nodes in the network can then take advantage of this information to select routes avoiding malicious nodes. In our case, the anchor nodes which have been formerly used for nodes localization (see Section 5.2.2 for more details), naturally become "cluster heads" for the purpose of distributing security related information, since they are:

- Less vulnerable than any normal node in the network, for they do not directly participate in data transmissions (output only);
- Already deployed in the network, it would be more economic (in terms of both energy and cost) to add some non-heavy duty task to them rather than deploying additional nodes for information distribution.

5.4.3 Route Discovery Based on AHP

After the security information have been distributed around the network, the next step is to utilize these information to discover the optimal routes with the help of Analytic Hierarchy Process (AHP) [41]. AHP is one choice of multi-criteria decision analysis (MCDA) methods, which are developed to help making decisions (in our case, choosing the best route) under multiple concerns (e.g. energy efficiency, security). There are other candidates besides AHP, but none of those candidates (including AHP) is perfect and cannot be applied to all problems.

In the case of this chapter, the "utility function" (which has been introduced in Section 4.3.2) of each route is hard to construct. It is because the Vampire attackers still deliver the packet eventually, thus in a sense, the energy consumed by attackers cannot be considered as “completely” wasted. Furthermore, as addressed in Section 5.2.1, the extra energy consumption caused by Vampire attacks depends on some random parameters, it varies a lot and its exact volume is hard to estimate, which brings even more difficulties for constructing the utility function. As suggested by the authors of [41], AHP is particularly useful when the decision maker is unable to construct a utility function.

Then we can set the goal to find out the optimal route based on multiple criteria, as shown in Figure 5.5. The top element is the goal of the decision, the second level of the hierarchy represents the criteria, the lowest level represents the available choices (routes). Following this figure, the scores, or so called priorities, of different choices of routes, are calculated based on the pairwise comparisons between different criteria provided by user.

5.4.4 Details of AHP

In AHP, pairwise comparisons are made between different criteria, thus ratio scales are needed. The judgement is a relative value or a quotient w_1/w_2 of two quantities w_1 and w_2 (in our case w_1 and w_2 are security concern and energy efficiency concern). In other words, these relative values (or ratio scales) represent the priority (importance) of each criterion.

Table 5.3 shows the most straightforward linear priority setup proposed by Saaty [93]. There are 9 degrees of priority because a human being cannot simultaneously compare more than 7 subjects (± 2) [68], i.e. we are unable to assign proper importance to more than 7 items (± 2). This is the limitation of human being when processing information. To avoid confusion, we choose 7 + 2 = 9 degrees.

There are other choices as shown in Table 5.4. All these choice are based on psychophysics theory. The validity of each one in decision making is usually evaluated by experiments. In fact which scale provides the best performance is controversial, experiments results reveal that they are better than the basic linear one [64, 87, 96].

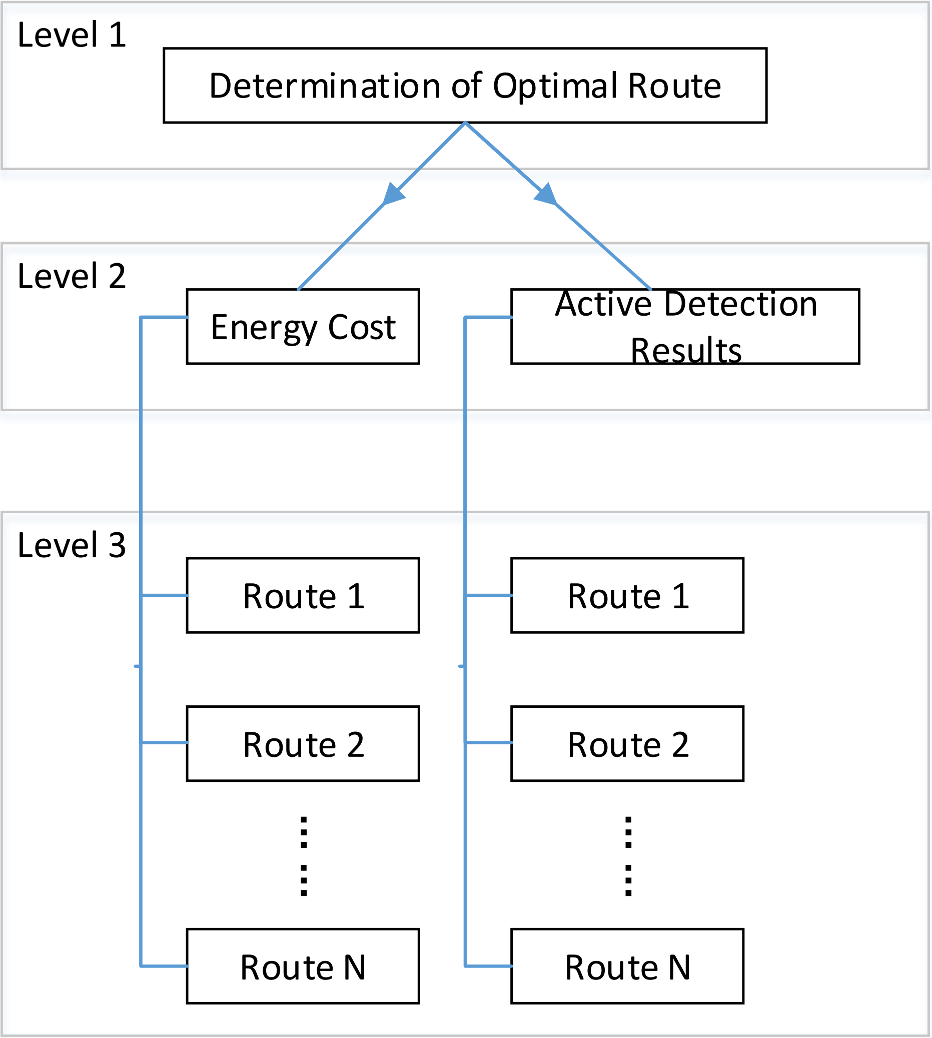


Fig. 5.5 Problem structure

Example: consider two routes evaluated according to two criteria, the energy efficiency and safety level. The security concern is considered twice as important as the energy efficiency. Suppose Route 2 is 2.5 times as safe as Route 1, and with transmission cost that is double compared to Route 1. The two routes can be compared on a ratio scale:

$$\frac{\text{Route 2}}{\text{Route 1}} = 2 \cdot \frac{100\%}{40\ \%} + \frac{50\%}{100\%} = 5.5 \tag{5.13}$$

Therefore, Route 2 is 5.5 times as good as Route 1.

Table 5.3 Degree of priority (importance)

Degree of Importance	Definition
1	Equal Importance
2	Weak
3	Moderate Importance
4	Moderate Plus
5	Strong Importance
6	Strong Plus
7	Very Strong or demonstrated Importance
8	Very Very Strong
9	Extreme Importance

Table 5.4 Different scales of priority setup

Scale Types	Equal Importance	Weak	Moderate Importance	Moderate Plus	Strong Importance	Strong Plus	Very Strong Importance	Very Very Strong	Extreme Importance
Linear	1	2	3	4	5	6	7	8	9
Power	1	4	9	16	25	36	49	64	81
Geometric	1	2	4	8	16	32	64	128	256
Logarithmic	1	1.58	2	2.32	2.58	2.81	3	3.17	3.32
Square Root	1	1.41	1.73	2	2.23	2.45	2.65	2.83	3
Asymptotical	0	0.12	0.24	0.36	0.46	0.55	0.63	0.70	0.76
Inverse Linear	1	1.13	1.29	1.5	1.8	2.25	3	4.5	9
Balanced	1	1.22	1.5	1.86	2.33	3	4	5.67	9

For an interval scale as below:

$$\text{Route } 2 - \text{Route } 1 = 2 \cdot (100\% - 40\%) + (50\% - 100\%) = 0.7 \tag{5.14}$$

This also shows Route 2 is better.

To derive priorities of each route, verbal comparisons must be converted to numerical ones; details are given in the Section 5.4.5.

5.4.5 Priority Calculation in Optimal Route Determination

Suppose on any chosen i-th route with total number of J_i nodes, the expected total priority $P_y(i)$ can be calculated as

$$P_y(i) = P_y(i,1) + P_y(i,2) + ... + P_y(i,J_i - 1)) \tag{5.15}$$

where $P_y(i,m)$ is the priority from the m-th node on this route to its next hop ($1 \leq m \leq J_i - 1$).

In order to judge different routes fairly, a “standard next hop” is defined: the next hop node is 100% not compromised, the distance to next hop node is the maximum radio range, and the transmission cost after a successful packet delivery to next hop node is E_{st}.

Similar to the example given in Section 5.4.4, the priority on each hop compare to the case of ’standard next hop’ is further given by

$$P_y(i,m) = P_{ey}(i,m) + I_s \cdot P_{sy}(i,m) \tag{5.16}$$

where $P_{ey}(i,m)$ is the priority (importance) of energy efficiency, inversely proportional to the normalised expected transmission cost (with respect to E_{st}, and please see Section 3.2.3 for how to estimate the transmission cost). Similarly, $P_{sy}(i,m)$ is the priority (importance) of security concerns, proportional to the possibility that the next hop node is not compromised (derived from Equation (5.10) in Section 5.4.1). I_s is the corresponding scale of security concern priority, indicating that security concern is considered I_s times as important as the energy efficiency concern. The exact volume of I_s could be picked from Table 5.4.

5.4.6 Optimal Route Determination

The optimal route is chosen with the maximum P_y interpreted as the safest route while keeping the least energy consumption possible.

Practical route discovery can be accomplished with existing routing protocols (such as AODV), with minor changes in the control messages such as RREQs and RREPs.

Specifically, the field “hop count” should be replaced with corresponding “priority volume count”. In RREQs, the “priority volume count” implies the total priority volume of the route from the originator node to the node handling the request. In RREPs, “priority volume count” denotes the priority volume of the route from originator node to the destination node. There is another minor change as well: AODV picks the route with minimum hops, the optimal route here is with the maximum priority volume.

5.5 Simulation Results

In this section, the performance of the RCPED routing protocol is analysed. Two competitors are chosen for comparison. The first protocol for comparison is PLGPa, which is dedicated to the mitigation of Vampire attacks based on the cryptographic approach. The other protocol for comparison is AODV-EHA, an energy efficient protocol aware of energy harvesting [31].

Overview of PLGPa

PLGP is a clean-slate secure sensor network routing protocol proposed by Parno *et al.* [78]. It consists of two phrases: topology discovery and packet forwarding. In the first phrase, all the nodes are organized in a tree, which can be further used for addressing and routing. In the second phrase, after transmission is initiated, each node chooses the node with maximum “logical distance (determined from the aforementioned tree)” from the source node as the next hop, which is aimed to make sure that the next hop would be closer to the destination node (in other words, try to shorten the logical distance to the destination as much as possible). PLGPa [110], a modified version of PLGP, can additionally provide the “no-backtracking” feature that can resist the Vampire attacks, at the cost of additional energy consumption caused by encryption.

Overview of AODV-EHA

An overview of AODV-EHA was given in Section 4.4.1.

Table 5.5 Simulation parameters

Parameters	Descriptions
Simulation Area	500 m $\times$ 500 m
Node Radio Range	250 m
Traffic Type	CBR
Packet Size	127 bytes
Data Rate	20 kbps
Signal to Noise Ratio (SNR) Threshold β	10
Processing Power Level P_c	10^{-4} W
Receiving Power Level P_r	5×10^{-5} W
Outage Requirement $\mathscr{P}^*_{out}(i,m)$	10^{-4}

5.5.1 Simulation Setup

The experimental evaluation is carried out by means of MATLAB simulations using the Monte-Carlo method. The criteria considered is the overall cost in which safety performance, average route length and energy efficiency performance are involved.

The size of the simulated area is 500 $m \times$ 500 m. The communication range of each node is 250 m. Considering the WSN applications that are the focus of this chapter (as addressed in the beginning of Section 5.1), IEEE 802.15.4 is chosen for the physical and data link layer, which is suitable for low data rate but very long battery life applications [39]. According to the specification mentioned in [39], the traffic type is CBR with a data rate of 20 Kbps, and the size of each packet is 127 bytes. Since the transmission cost prediction partly depends on previous work [95], therefore for those parameters required for the prediction process we continue to use same values as adopted in [95]. Details are listed in Table 5.5.

Every simulation contains a certain malicious fraction of the network nodes. These compromised nodes are located randomly in the simulation area, and they are assigned with certain behaviours that can further affect the route discovery process.

The destination node is assumed to be stationary, which complies the scenario in applications of enemy detection or environment surveillance, the engineer just stay at a fixed observation point in the region where the WSN is deployed, and collects data from the nodes. The nodes number varies from 60 to 200.

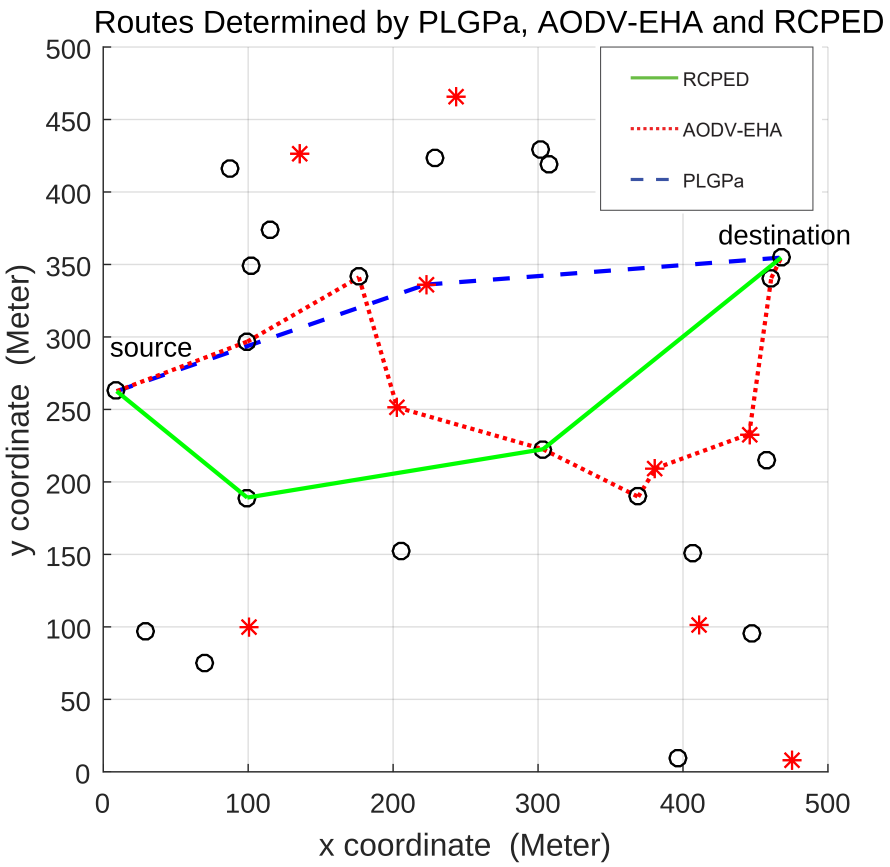


Fig. 5.6 Route determination example

5.5.2 Experimental Results

Figure 5.6 shows a simple example that demonstrates different routes determined by PLGPa, AODV-EHA, RCPED, receptively, in a network consists of 30 nodes. Normal nodes are represented by dark circle, compromised nodes are marked with red star. PLGPa tends to find the way with least distance, as encryption is utilized to deal with malicious behaviour of any compromised node, PLGPa does not have to bypass compromised nodes deliberately. AODV-EHA seeks for the most energy efficient route under the assumption that all nodes are honest, and it inevitably may contain some malicious nodes on the route. As mentioned earlier in this chapter, RCPED is initially designed to bypass nodes that are not safe, while trying to reduce the energy cost as much as possible (by choosing relatively energy efficient route).

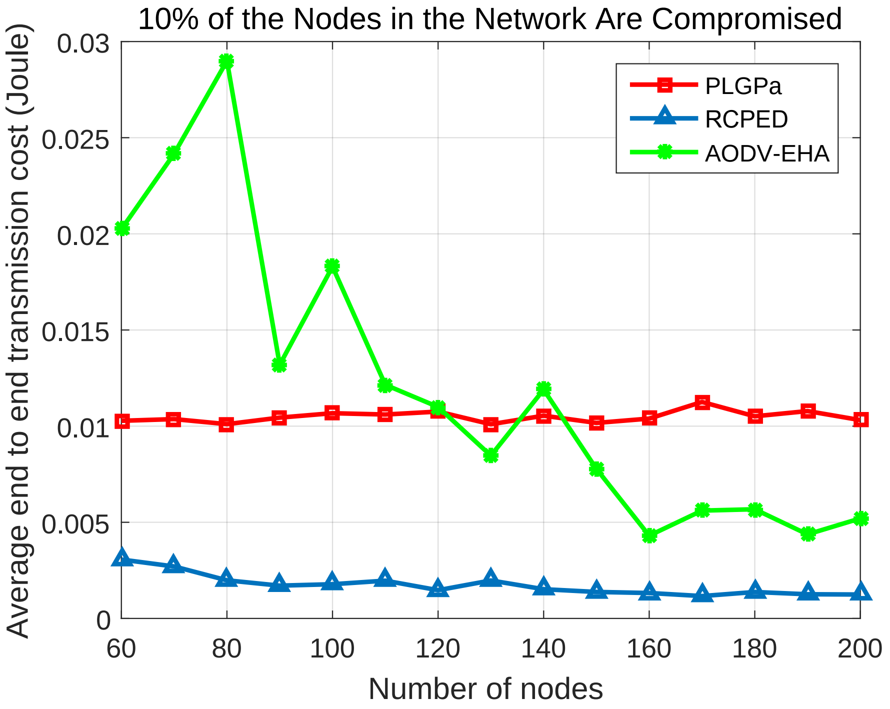


Fig. 5.7 Average end to end overall transmission cost (Joule)

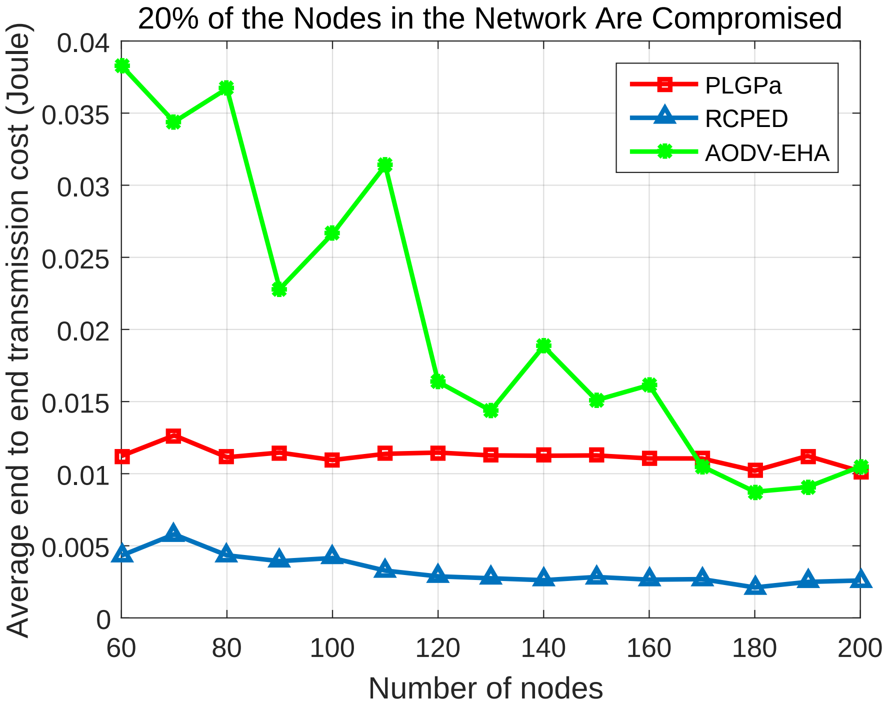


Fig. 5.8 Average end to end transmission cost (Joule)

Energy Efficiency Performance

Figure 5.7 – 5.9 show the average energy cost of each transmission (from arbitrary node to the observation point) at different malicious ratios (10% – 30%).

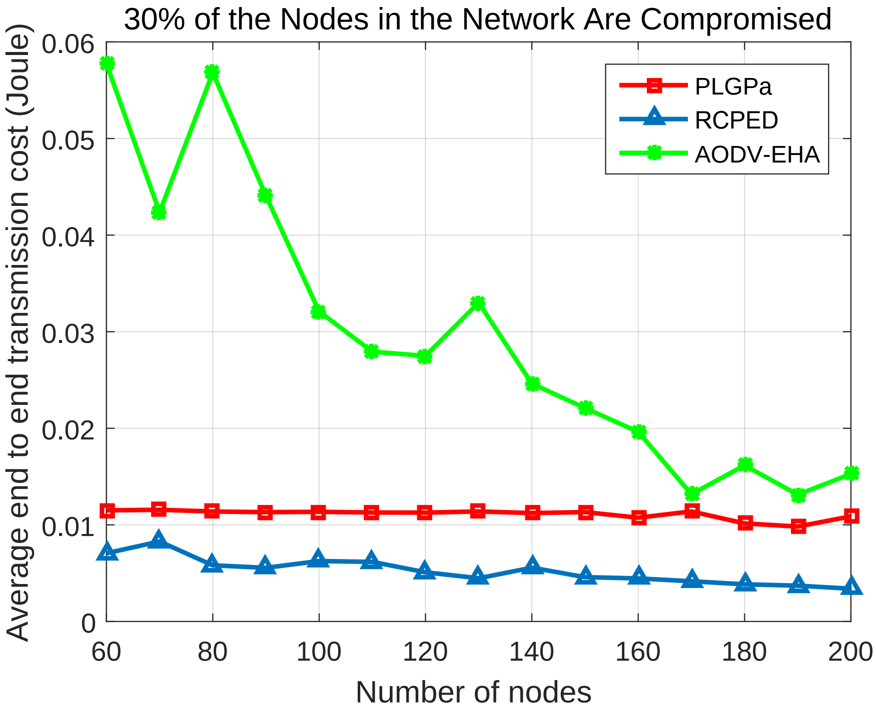


Fig. 5.9 Average end to end transmission cost (Joule)

For malicious ratio at 10% as shown in Figure 5.7, both lines of RCPED and PLGPa fluctuate per number of nodes in the network. RCPED consistently uses less average transmission cost compare to PLGPa, thanks to the fact that RCPED does not need additional hardware to grantee security (additional hardware requires extra energy consumption). In comparison to PLGPa, the energy cost reduced by RCPED can reach up to 87.93%. The average transmission cost of AODV-EHA tends to decrease as the nodes number increase, even it does fluctuate violently. The cost appears to be less than that of PLGPa when nodes number in the network is above a certain value (130 or higher). It is because the increment of nodes density provides more choices of nodes, and is more likely to find a more energy efficient route. Even though sometimes compromised nodes are included on the route (which make green line fluctuate violently), the damage can be compensated to some extent. Hence, when the choices of nodes are plenty enough (130 or higher), the compensation can be large enough to make AODV-EHA provide a better performance than that of PLGPa.

As malicious ratio rises to 20% (illustrated in Figure 5.8), even though RCPED is still the one with least average transmission cost, but its performance advantage over PLGPa begins to shrink. This is because it is more difficult for RCPED to eliminate compromised nodes in route discovery as the malicious ratio goes up, the aforementioned saved energy that comes with the independence of additional hardware could be counteracted to some extent. The tendency of AODV-EHA remains the same as that in Figure 5.7, but the transmission cost appear to be less than PLGPa only after nodes number reaches 170 and above, which is more than 130 at malicious ratio 10%. This is due to the fact that a larger malicious ratio make it more possible for AODV-EHA to encounter compromised nodes in route discovery, hence the aforementioned energy compensation that brought by the increment in choices of nodes is partially offset.

When malicious ratio goes up to 30% (as shown in Figure 5.9), energy cost reduced by RCPED compare to PLGPa continues to drop, sometimes goes down to 28.34%. The AODV-EHA keeps the same line tendency as previously appeared in Figure 5.7 and Figure 5.8, but its performance never overcome PLGPa in the given nodes number span (60 to 200). This is because, as malicious ratio continues to ascend, it is more and more difficult for protocols that are not equipped with cryptographic encryption (e.g. RCPED and AODV-EHA) to prevent the damage (extra energy cost) from compromised nodes.

From all the above results gained from overall energy cost performance evaluations, we can conclude that under different malicious ratios, RCPED has advantages in terms of overall energy cost in transmission. But its relative advantage over PLGPa tends to decrease as the malicious ratio of the network goes up.

Safety Performance

In performance evaluation, “safety performance” has been naturally converted part of energy efficiency performance given a specific malicious ratio, since all the damage come with Vampire attacks present in the form of more energy consumption. Thus, the overall cost is a comprehensive “energy overhead” which involves the estimated energy cost after successfully delivering a data packet, plus the extra energy consumption caused by the Vampire attacks in this transmission along the route discovered by a specific routing protocol. In other words, higher energy consumption means longer average route length in data transmission. The overall cost (or so called comprehensive "energy overhead") mentioned earlier can be considered as an indicator of safety level as well. Therefore, the earlier part of Section 5.5.2 has already presented an overall performance evaluation including both energy efficiency and safety performance.

Average Route Length

The evaluation of "average route length" has been naturally converted to part of average energy cost evaluation given a specific malicious ratio. This is because in the presence of Vampire attacks, routes are more likely to be with unnecessarily long length if the attacks take effect (in the form of more energy consumption). In other words, higher energy consumption means longer average route length in data transmission. The overall energy cost (or so called comprehensive "energy overhead") mentioned earlier can be considered as an indicator of route length as well. Therefore, the earlier part of Section 5.5.2 has already presented an overall performance evaluation including both energy efficiency and average route length.

Effect of Buffer Size

Figure 5.10 – 5.12 show the performance of RCPED with different data buffer size at various malicious ratio.

For malicious ratio at 10% as shown in Figure 5.10, the advantage of utilizing larger buffer is not very distinct. In many cases the performance lines (represents the of transmission cost) wind around each other. On the other hand, as the nodes number in the network increases, the transmission costs of RCPED with different buffer size are with decreasing tendency, but fluctuations (sometimes violent) still exist.

As malicious ratio rises to 20% (illustrated in Figure 5.11), the advantage of adopting larger buffer size becomes a bit clearer, in most cases larger buffer size brings less energy cost in data transmission. The descending tendency of transmission costs with different buffer size still remains, and the fluctuations seem less violent.

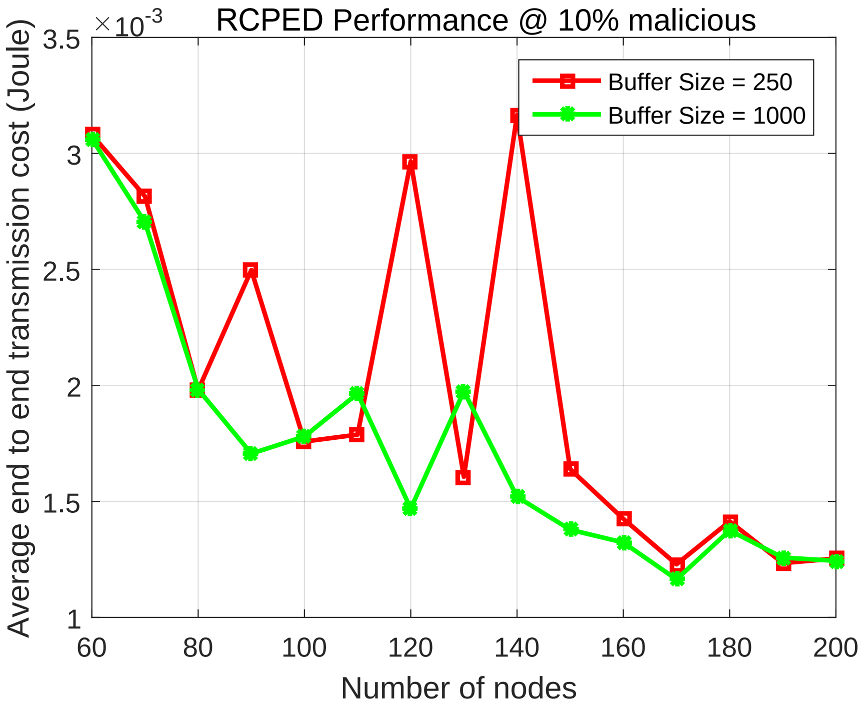


Fig. 5.10 RCPED performance with different buffer size

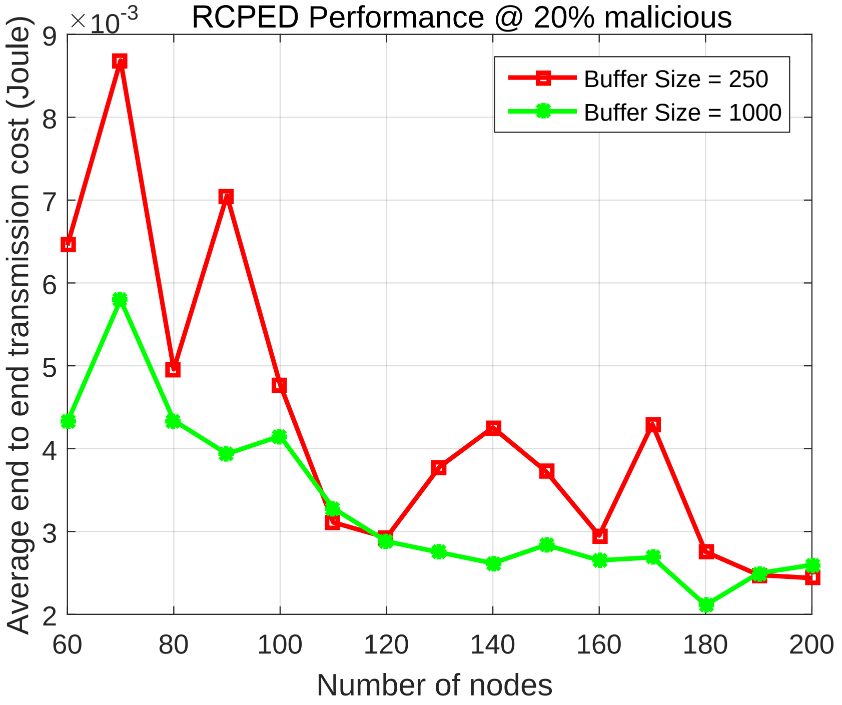


Fig. 5.11 RCPED performance with different buffer size

When malicious ratio goes up to 30%, the advantage of adopting larger buffer size becomes apparent. But the fluctuations in transmission cost lines of different buffer size still have no sign of being eliminated.

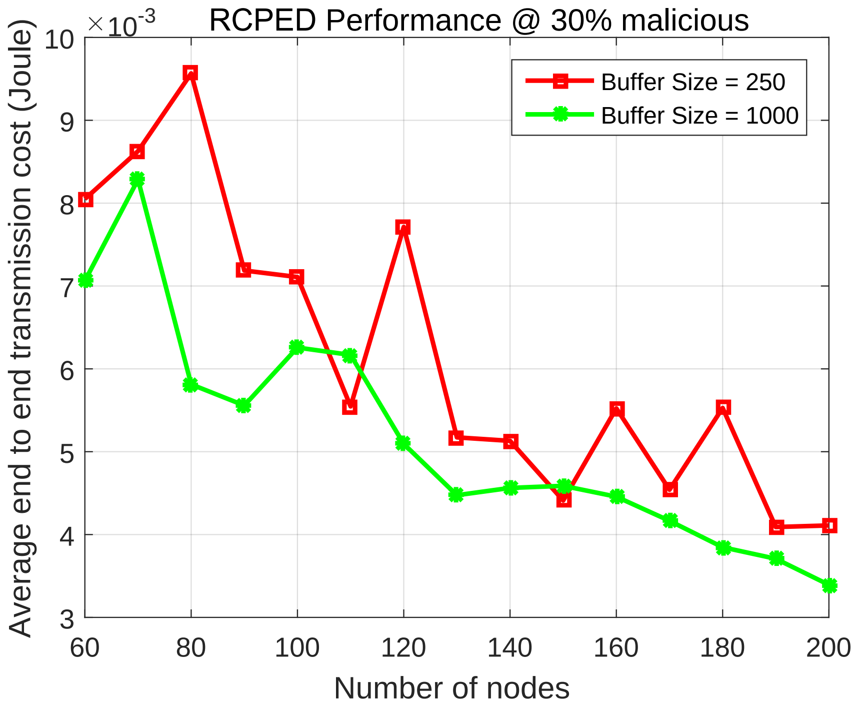


Fig. 5.12 RCPED performance with different buffer size

Then it can be concluded that, RCPED generally achieves better performance with larger buffer size, but the advantage is not clear when the malicious ratio is low. As the malicious ratio of the network grows, this advantage becomes increasingly clear.

5.6 Summary

In this chapter, we introduced the RCPED for the WSN applications under the threats of Vampire attacks. RCPED continuously looks for abnormal signs of network behaviour, and aims to protect it from energy draining if the existence of Vampire attacks is confirmed. Simulation results show that under various malicious ratios, RCPED achieves the minimum overall energy cost, which reflect the energy efficiency performance and performance metrics simultaneously.

Chapter 6

Summary and Future Work

6.1 Dissertation Summary

This main aim of this dissertation is to improve routing protocols in WSNs to ensure efficient energy usage and protect them against attacks. After studies on previous literatures, we discovered that the nominated WSN applications in this dissertation have two distinct common features: with uncertain network topology (ad hoc nature) and nodes are unreachable after deployments (sensitive to energy). The traditional routing protocols have made some effort to cope with the two aforementioned features, unfortunately, just solely with either of them.

Thus, in the first phase of this dissertation, we focused on investigating how to deal with the two aforementioned common features simultaneously. Therefore we are motivated to propose AODV-EHA, that can deal the two features simultaneously. For ad hoc nature, we chose to take full advantage of existing AODV, bring no extra complexity and routing overhead. For improving energy efficiency, since previous studies have tried very hard on this issue by means of improving routing protocols themselves, we took an alternative path, by introducing energy harvesting capability as external energy source to the sensor nodes. Even though there are some attempts have taken energy harvesting into consideration, such as DEHAR, but its modelling of transmission cost (based on the concept of "energy distance") is relatively less accurate than that of AODV-EHA.

Simulation results have proved that AODV-EHA has advantages over its competitors in terms of energy cost for data packet delivery, at the cost of longer routing path.

Another discovery from the studies on previous literatures is, as the nominated WSN applications might be utilized for military purpose, therefore security becomes another crucial concern, in addition to energy efficiency. Basically energy efficiency and security are different issues, and routing protocols are usually proposed separately for them. Even though there are a few trails starting to consider them at the same time, but the drawbacks are apparent, e.g. dependence of cryptographic encryption that brings extra overhead or even requires extra hardware. Thus, we were motivated to figure out an “untraditional” way to deal the two issues at the same time.

Then ETARP, which makes a novel use of utility theory, was proposed. Utility theory is originally from Microeconomics, which can help to simultaneously consider two factors: energy efficiency and trustworthiness of nodes. Specifically, trustworthiness of nodes was calculated with the help of Bayesian network. Unlike the existing reputation management which only watches a specific node behaviour, a Bayesian network is meant to organize the entire knowledge about observed node behaviours into a coherent whole.

Results have revealed that ETARP has the advantages over competitors in terms of energy efficiency in transmissions, while it can still maintain about the same safety performance as some existing secure routing protocols (e.g. LTB-AODV).

At last, we shifted our attentions to a type of resource depletion attack, Vampire attacks, which are specifically targeting energy efficiency of routing protocols for WSNs. To the best of our knowledge, there are very few routing solutions can offer protection against Vampire attacks. Even worse, these limited choices (e.g. PLGPa) highly depend on cryptographic methods, that require additional computation cost and hardware. As we know, wireless sensor nodes are with limited energy storage and computation capability. In this case, how to maintain the energy efficiency of WSN applications under the threats from Vampire attacks, at minimum extra cost is worth investigating.

Therefore, in order to provide an energy efficient routing protections, RCPED protocol was proposed. It was designed to collaborate with existing routing protocols, perform detections on abnormal sign of attackers, and provide routing protection independent of cryptographic methods against Vampire attacks (by selecting the routes with maximum priority, i.e. the routes with best overall energy efficiency and security performance). Experiment results have demonstrated that RCPED protocol achieves the minimum overall energy cost, compare to its competitors (e.g. PLGPa).

6.2 Future Work Directions

In this dissertation, the main aim is to design energy efficient and secure routing solutions supporting nominated WSN applications, especially when they are deployed in extreme environments. Analytic and simulation tools have been developed to understand the problem and several approaches have been investigated to mitigate the adverse consequences that come from limitations of wireless sensors and external attacks.

In the future it is believed that there are several problems worth investigating, which are:

- First, adoption of multi-resources energy harvesting. A recent publication [27] shows that rather than extracting energy from a solo resource, some newly produced energy harvesting modules can have more than one harvesters, it implies that collecting energy from various sources (such as solar, motion, thermo, and so on). But the analytical model for the multi-resources energy harvesting needs to be established, and then merged into the route discovery process.

- Second, adoption of novel energy harvesting resources: such as from green plants all around the earth [55] and ambient RF signals everywhere in the air [29]. And it can be predicted that there will be more and more new resources emerge in the future, and to determine the analytical models of them are necessary, or we cannot see how will they impact the routing process.

- Third, the RCPED protocol still requires nodes locations for monitoring process, to provide a security solution without cryptographic authentication. Due to the limitations of space, computation capability and energy storage on wireless sensor nodes, it is worth researching on a monitoring method independent of cryptographic authentication while requiring as less extra information (such as regardless of nodes locations) as possible.

- Fourth, rather than letting all the detection works be concentrated at the observation point (centralized monitoring), the monitoring process could be carried out at any honest node in the network distributively (distributed monitoring). Results could be more accurate if we can extract information directly from the place where WSNs are exactly deployed, thus reliable and energy efficient detecting methods need to be figured out.

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List of Publications

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[2] P. Gong, T. Chen, and Q. Xu, "ETARP: An Energy Efficient Trust-Aware Routing Protocol for Wireless Sensor Networks", in *Journal of Sensors*, Volume 2015, Article ID 469793, Jan. 2015.

[3] P. Gong, Q. Xu, and T. Chen, "RCPED: An Resource-Conserving Protection Against Energy Draining Protocol for Wireless Sensor Networks", under *Peer Review*, Feb. 2016.