ENERGY-EFFICIENT AND RELIABLE COMMUNICATION IN WIRELESS SENSOR NETWORKS

Theses of the Ph.D. dissertation
Thesis booklet for Ph.D. dissertation

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1 Introduction and objectives

Present day info-communication technologies are in great need for algorithms, which can optimize and further extend the network performance. There are several platforms and application domains (e.g., Internet of Things (IoT), Artificial Intelligence (AI) Cloud Computing) whose performance requires novel optimization methods in improving the reliability, outlier detection and Quality-of-service (QoS) routing in data transmission. To be known as a subset of IoT, the Wireless Sensor Network (WSN) consists of hundreds or even thousands of small, inexpensive wireless nodes that are deployed in sensing field. These wireless nodes are able to sense events and communicate with neighbor nodes by wireless connectivity with high economic value. Furthermore, WSN may be deployed in some rough terrains where some traditional IoT devices cannot work properly. For example, some endpoint devices in IoT (e.g., security cameras, mobiles, smart watches, computers, cars, robot, industrial machines) cannot connect to a network without supporting of well-designed infrastructure. Fortunately, by using some special routing protocols, each tiny node in WSN (sometimes called as dust networks or smart dust networks [18, 19]) is capable of sensing its environment, locally processing data, and transmitting data to the collection devices with high reliability and in short execution time. As a result, WSNs have been emerged as one of the most promising technologies for a number of applications, such as military applications, industrial applications, agricultural applications, health applications, as well as numerous consumer applications. By using a WSN, we can sense and collect data
from the world around us for monitoring [20, 21], healthcare monitoring [22, 23], controlling [24], managing systems [25] or many other purposes. However, despite many years of development, the WSN still faces many challenges, mainly caused by its constrained resources such as limited power, short radio transmission range, narrow radio bandwidth, and limited memory capacity. These limitations directly affect the network performance including network lifetime, network reliability, and Quality of Service (QoS) in real-world applications. Therefore, the critical requirements of these applications are low data transmission cost, long network lifespan, and high reliability communication. To satisfy these requirements, a large number of works has been done in a WSN, such as to minimize the energy consumption, to maximize the network lifetime, to increase the probability of successful packets in data transmission, as well as, to detect outliers in raw sensing data from various wireless sensor nodes.

The objective of my research is to provide new and efficient solutions, which minimize the system cost, decrease the transmission overhead, improve the network lifespan and maximize the system reliability in WSNs. These solutions are described in solving the problems in five specific domains:

- the problem of finding the optimal resource management and packet scheduling in WSNs;
- the problem of maximizing the network lifetime in Mobile Wireless Sensor Network (MWSNs);
- the problem of improving the QoS routing;
● the problem of prediction-based outlier detection for WSNs;
● and localization problem in Non-Light-of-Sight (NLoS) environments.

Although these five domains may seemingly be classified into different areas, they altogether have a great impact on the efficiency of WSNs. The algorithms and methods proposed in my dissertation can also be used in other applications such as public transport control and guidance systems, financial computational systems, etc. The next section summarizes the technological background, motivations, and state-of-the-art of each topic.

1.1 Resource management and packet scheduling

The wireless sensor nodes are battery-powered and it is proven that a sensor node spends more than 50% of its energy for communication activity [6]. Therefore, minimizing energy consumption in data transmission is one of the primary concerns in WSNs applications. In the first thesis, I investigated the optimal resource management and packet scheduling in WSN communication. I introduced a new efficient approach to transmit data with low energy consumption by developing a smart scheduler. The proposed algorithm not only achieves a low runtime complexity but also guarantees a predefined probability of packet loss. Furthermore, our algorithm can work well in WSNs by using Orthogonal Frequency Division Multiplexing (OFDM) systems.
1.2 Maximizing the network lifetime in Mobile WSNs

Recently, the rapid development of robotics, sensor structure, and wireless communication techniques make feasible to improve the network lifetime in Mobile Wireless Sensor Networks (MWSNs). Many authors [7–11] have tried to extend the network lifetime by mobility in WSN, but none have really succeeded in proposing a successful operating cycle of a MWSN wherein a signal is generated, collected, and analyzed. In the second thesis, I investigated how data is collected and how to plan the trajectory of the MS in order to gather data in time with small energy consumption and long network lifetime. I proposed a new algorithm to find the optimal trajectory of mobile sinks, by which the energy consumption and running time in a closed operating cycle of a WSN are minimized.

1.3 Improving QoS routing for WSNs

Efficient and secure data transmission is a critical issue in WSNs. It is necessary to provide an energy efficient, low latency, high-reliability routing protocol for WSN in order to enhance the network lifetime and stability. This routing protocol also should solve the bottleneck path problem for achieving better performance and economics in data communication in WSN. In the third thesis, I investigated the QoS routing protocols for WSNs. I proposed a new algorithm to find the optimal path routing from the Source Node (SN) to the Base Station (BS), by which a packet data is received successfully at
the BS with minimum energy consumption under a reliability constraint.

1.4 Outlier detection in WSNs data

In many applications, a huge of data from a number of nodes will be received by the BS. There are still several outliers or noisy data, which may result from the architect of sensors, sensor employment policies, human-related errors, and/or sudden change of the environmental parameters. The outliers might seriously affect the accuracy of data analysis which causes model misspecification. Considering the importance of outlier detection, in the fourth thesis, I investigated the outlier detection in the streaming data. I developed and proposed a new outlier detection method, which is based on the probability of the order error. My proposed algorithm can detect and remove outliers on-line from measurement records of wireless sensor nodes.

1.5 Position location technique in Non-Line-of-Sight (NLoS) environment for WSNs

Localization of every sensor node in the network plays a critical role in many WSN applications such as in (i) coverage, (ii) event detection, and routing designing [12–15]. Therefore, in the fifth thesis, I focused on developing some position location techniques in NLoS environments for WSN, which achieve high accuracy in location detection with small execution time.


2 The objectives of the dissertation

Concluding the previous section, the objective of the dissertation is to develop algorithmic tools, which are given in Table 1.

Table 1: Summary of research areas and theses

<table>
<thead>
<tr>
<th>Research area</th>
<th>WSN applications</th>
<th>Further applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource management and packet scheduling</td>
<td>Packet scheduling, Lan protocols</td>
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</tr>
<tr>
<td>Maximizing the network lifetime in Mobile Wireless Sensor Network</td>
<td>Cluster head election in WSN, Efficient mobility technology in WSNs</td>
<td>Optimize movement schedule, Traveling salesman problem applications</td>
</tr>
<tr>
<td>Improving QoS routing for WSNs</td>
<td>Efficient routing technique for WSN</td>
<td>Quality of Service in telecommunication networks</td>
</tr>
</tbody>
</table>

Continued on next page

6
3 Methods of investigation

In order to achieve the results presented in the dissertation, the following models and computational methods have been used and developed. A detailed summary of the methods is presented in Table 2. All models and methods implementations were performed in MATLAB software, where numerical simulations were run on both synthetic and real-world datasets. The processing details are given in Figure 1.
<table>
<thead>
<tr>
<th>Thesis</th>
<th>Used models</th>
<th>Applied methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.</td>
<td>Neyman-Pearson</td>
<td>Orthogonal Frequency Division Multiplexing method</td>
</tr>
<tr>
<td>II.</td>
<td>The balance between the energy residual and the energy consumption in one cycle operation. Multiple traveling salesman problem</td>
<td>The Cluster Heads Election Algorithm (CHE), The MS trajectory optimization (MSTO) algorithm, The Optimal Movement Strategy (OMS) for MS</td>
</tr>
<tr>
<td>III.</td>
<td>Rayleigh fading</td>
<td>Bellman-Ford algorithm</td>
</tr>
<tr>
<td>IV.</td>
<td>Auto-regressive AR(L) model</td>
<td>The probability of the First Order Error (FOE)</td>
</tr>
<tr>
<td>V.</td>
<td>Range-based model to detect the location of sensor nodes</td>
<td>Expected Position Circle Scan (EPCS), Steepest Ascent Search (SAS), Stochastic Gradient Ascent (SGA), and Simulated Annealing (SA) methods</td>
</tr>
</tbody>
</table>
4 New scientific results

4.1 Scheduling algorithm

4.1.1 Thesis

I have developed a new algorithm to solve the resource management problem based on OFDM system. The new algorithm is developed based on the multi-carrier transmission technology to schedule data transmission in wireless and Ad hoc networks. This algorithm has many applications, which tries to allocate or assigns some limited resources to tasks when considers its capacity during each period of time. I implement this algorithm for dynamically finding the optimal schedule to collect a large number of packets from sensor nodes to the BS with minimum system cost while ensuring a given probability of
successful data packets at the BS (Chapter 2 of the Thesis).

(The publications connected to this thesis are: [1].)

In some real applications, a large amounts of data need to be transferred from source nodes to destination nodes with “Timely delivery ” and “Guaranteed delivery ”. To satisfy these requirements, I focus on utilizing the OFDM system in data communication in WSNs. One can formulate the optimal scheduling problem as finding the optimal vector $\mathbf{y}_{\text{opt}}$ for which:

$$\mathbf{y}_{\text{opt}} : \min_{\mathbf{y}} \sum_{k=1}^{K} \sum_{m=1}^{M} y_{mk} c_m$$

subject to the constraints:

$$C_1 : P \left( \sum_{k=1}^{K} \sum_{m=1}^{M} \xi_{mk} \geq X_k \right) \geq 1 - \gamma$$

$$C_2 : \max_l y_{mk} \leq K_f$$

where $y_{mk}$ is the number of packets are assigned to sub-carrier $m^{th}$ by Node $m$, $c_m$ is the required transmission power for allocating packets to sub-carrier $S_m$, $\xi_{mk}$ denotes the number of packets sent on sub-carrier $S_m$, $X_k$ indicates the number of packets needed to be transmitted, $\gamma$ is the reliability threshold, and $K_f$ is the number of available carrier frequencies in a sub-carrier.

These objective and constraint functions can be solved by using the following properties:

**Property 1:** The system reliability will be increased when moving a packet from sub-carrier $S_H$ to its neighbor $S_{H+1}$.

**Property 2:** The system reliability will be increased when
Figure 2: Flowchart of optimized cost scheduling algorithm
sending a new packet in sub-carrier $S_1$. Based on these properties, I have created a new packet scheduling protocol for WSNs, which improves the system reliability and minimizes the system cost and runtime complexity. The flowchart of this algorithm is given in Figure 2.

4.1.2 Performance analysis of the methods introduced in the first Thesis

In order to evaluate the performance of my proposed algorithm, I conducted some experimental studies with different number of sub-carriers ($M$) and a different number of packets needed to be sent. The performances of the algorithms are depicted in Figure 3 when comparing the system cost between the proposed algorithm and a typical algorithm.

When assigning a number of packets to each sub-carrier randomly as be done by random scheduling (RS) algorithm, the average of the system cost is from 2 to 10 times higher than the cost of my proposed algorithm. It means that my algorithm achieves at least 50% reduction on energy consumption, therefore, it can prolong the network lifetime.

Figure 4 depicts the improvement in system reliability of my proposed CMS algorithm compared to RS algorithm. Herein, the system is set with $(X, M) = (25, 10)$ and the expected transmission system reliability is 0.999.

Figure 5 illustrates the comparison of the data rates in communication by CMS algorithm and some previous well-known algorithms.
Figure 3: The comparison of the system cost between RS algorithm and CMS algorithm

Figure 4: The improvement in system reliability with \((X, M) = (25, 10)\)
Figure 5: The comparison of data rate in communication

It is shown that the data rate by CMS algorithm is slightly lower than the results of the algorithm proposed by Kim et al. However, it is still better than that of some other algorithms.
4.2 Maximizing the network lifetime in MWSNs

4.2.1 Thesis

I have combined two methods (i.e., the cluster-head election algorithm and the MS trajectory optimization algorithm) to propose the optimal MS movement strategy. Firstly, the best candidate node in a cluster, which has both high energy residual and short path length from a candidate node to all member nodes in that cluster, is elected as a Cluster Head node (CH). Secondly, two scenarios for optimizing the MS trajectory are carefully analyzed. The optimal trajectory of the MS is obtained when both minimizing energy consumption and the constraint time in data gathering are met. It showed that my proposed algorithms adapt well to the different network sizes, improves the network lifespan, and exhibits better performance than some typical algorithms.

(The publication connected to this thesis: [3].)

A. Cluster heads election problem in WSNs

I have proposed a new technique to find the best candidate for cluster head node, by which a member Cluster Node (CN) will become a CH if it has the maximum priority value $PV_k$.

$$PV_k = \max \left\{ \frac{1}{l_k} + \beta \frac{E_k(t)}{E_0} \right\}, k = 1, \ldots, N_i$$

(3)

Where $\alpha, \beta$ are positive real numbers such that $\alpha + \beta = 1$, and called weighting factors. $E_0$ is the initial energy of node $S_k$. In
this way, one normal node is elected as a CH if it not only has a high residual energy but also the energy balance among all the nodes in the network is assured. The CH election procedures for each area can be described more in detail in Figure 6.

B. Optimizing the trajectory of the mobile sink
In this subsection, I present the MSTO algorithm, whose basic idea is to investigate the path with the smallest time spending for traveling and gathering data. Let $K_{\text{min}}$ denote the number of the MS are used in data collection, $\xi_0$ is a threshold of reporting time, and $R$ indicates the data transmission rate of the MS. It will be an efficient data gathering scheme without loss of sensed data if only if

$$\frac{1}{K_{\text{min}}} \left( \frac{\mathcal{R}(t)}{v(t)} + \frac{mN}{R} \right) \leq \xi_0$$

where $\mathcal{R}(t)$ is the total path length of $M$ CHs in the network and $v(t)$ is the velocity of the MS at current round $t$. If $\xi_0$ is high enough, we can utilize a single MS with constant velocity to harvest all captured data from $N$ nodes in order to reduce the communication cost. Unfortunately, it is generally not enough time for collecting all sensed data by a single MS. In these situations, I presented two solution scenarios: (i) Scenario 1 (OMS1) - change the speed of a single MS; (ii) Scenario 2 (OMS2): utilize more than one MS to collect data. The flowchart of the optimal movement strategy for MS is given in Figure 7.
Figure 6: Flowchart of the CHE algorithm

Start

Step 1
Choose new sub-area for cluster-head election

Step 2
- Let a CN ($S_k$), which hasn’t got its priority value, become a candidate node.
- Find the shortest path from candidate node to all CNs.
- Calculate the priority value of candidate node

$$PV_k = \left\{ \alpha \frac{1}{l_k} + \beta \frac{E_k(t)}{E_0} \right\}$$

Step 3
All CNs have their $PV_i$?

Step 4
$S_k$ becomes CH for chosen sub-area if $PV_k = \max\{PV_1, ..., PV_N\}$

Step 5
All areas have CH?

End
Figure 7: Flowchart of the optimal movement strategy for MS

1. Cluster-head election by CHE algorithm;
2. Choose cluster for each CNs;
3. Transmit of forward data to CHs;
4. Find minimal spanning tree;
5. Collecting data and compute the residual energy of each CN;
6. \( \min_{1 \leq k \leq N} E_k(t) \geq \theta \)

Scenario 1: Use single MS for data collection and change its velocity.
Scenario 2: Keep the velocity of the MSs low, and increase the number of

Find optimal trajectory of the MS
4.2.2 Performance analysis

A. Cluster head election problem
The performance of CHE algorithm was evaluated and compared with the method proposed in [16] and [17] when changing the network size. In Figure 8, it is proved that the CHE algorithm prolongs the network lifetime up to 12% and 29% when compared it with Impro-LEACH and LEACH (Low-Energy Adaptive Clustering Hierarchy) algorithms, respectively.

![Figure 8: The improvement in network lifetime by cluster head election](image-url)
B. Performance analysis of the mobile sink trajectory optimization algorithm

As shown in Figure 9, my proposed schemes (OMS1 and OMS2) achieve longer lifetimes than the three other strategies (e.g. Moving along network boundary scheme, Stationary scheme, and Random scheme). OMS1 and OMS2, with the controlled mobility, avoid the hot-spot problem completely, which is the main reason for short network lifetime in the stationary scheme and fixed-trajectory schemes.

Figure 9: The comparison of network lifetime with different node densities
4.3 Increasing the efficiency of routing techniques for WSN

4.3.1 Thesis

I have developed new Routing protocol for WSNs to find the optimal path from source nodes to the BS. Unlike with traditional methods, I focused on minimizing the energy of a route while achieving a given threshold of reliable communication in WSNs. In this way, my proposed algorithm achieves significantly better in reliable data transmission and energy balance routing protocol than some typical algorithms. (The publication connected to this thesis: [1, 4].)

The energy state of the WSN is represented by vector $G$ where components $G_i, i = 1, \ldots, |V|$ indicate the available energy on node $i$. The transmission energies of the nodes are taken from a discrete set $g_i \in \{\Delta_1, \ldots, \Delta_L\}, i = 1, \ldots, |V|$. The flowchart of my proposed High Quality of service Routing Algorithm (HQRA) algorithm is given in Figure 10.

4.3.2 Performance analysis of the efficient routing techniques in WSN

My proposed routing protocol is able to find optimal paths in WSNs by minimizing the energy route and achieves a given level of reliability, as well. Figure 11 indicates the comparison of energy balancing among sensor nodes in the network. All the sensor nodes by HQRA algorithm used up almost all their energies in order to prolong the lifespan, while by Power
Figure 10: Flowchart of the HQRA algorithm

Step 1
Choose the smallest transmission energy $\Delta_1$.

Step 2
Find the best reliable path with the choice of transmission energy $R_{opt}$.

Step 3
$\prod_{i=1}^{M} P_{ij} \geq 1 - \varepsilon$

Step 4
Yes
Obtain a reliable path with uniform remaining energy.

Step 5
Increase the transmission energy $g_i = G_i - G_{min}$, where $G_{min} = \min\{G_i, i=1:V\}$

End
Efficient Data gathering and Aggregation Protocol (PEDAP), there are not many nodes ran out of energy before the network becomes disconnected.

Figure 11: Comparison of the energy consumption in network

4.4 Detecting outlier values and events in sensor readings

4.4.1 Thesis

*I have developed a new algorithm (my Outlier Detection method is based on the Probability of the Order Error (ODPOE)),*
which detects outlier values and events in sensor readings with high identification rate. Based on the probability of the first order error, this method can detect anomaly values and then reduces the number of data packets needs to transmit on the network; Consequently, the energy consumption of each sensor node reduces significantly. Furthermore, this method is able to detect and remove outliers online from measurement records of wireless sensor nodes. In this way, it can be widely used in some other applications such as detecting the violations of the network, fraud detection in the communication network, in banking systems.

The flowchart of ODPOE algorithm is given in Figure 12.

4.4.2 Performance analysis of the outlier detection method

The performance improvement of my algorithm is illustrated by comparing with a well-known typical outlier detection algorithm the Hampel Identifier (HI). As depicted in Figure 13, when increasing the percentage of outliers in time series (rank from 5% to 100%), the identification rates of both two algorithms reduce significantly. However, in all these cases, my proposed algorithm still achieves better performance than HI algorithm.

By detecting anomaly data flows of any IP addresses in the network, my proposed algorithm can distinguish when and where an attacker attacks the victim IP in the private network. The results of outlier detection in traffic flow within the network by the ODPOE algorithm is given in Figure 14.
Figure 12: Flowchart of the ODPOE algorithm
Figure 13: The comparison of identification rate in outlier detection

4.5 Position location technique in non-line-of-sight (NLoS) environment for WSNs

4.5.1 Thesis

I have developed new methods, which locates the sensor nodes positions with a high degree of the localization accuracy. The developed methods can reduce the execution time, therefore, it saves power and reduces the drop packet ratio. Furthermore, based on the Received Signal Strength (RSS), my algorithm
The bandwidth used by Users in the network is able to work efficiently in the NLoS environments. In this way, it is extensively used in many WSN applications. (The publication connected to this thesis: [2].)

The method of steepest ascent search (SAS) is a method to determine the absolute geographical location of sensor nodes based on the steepest ascent path of RSS. The basic idea of this method is described by the flowchart given in Figure 15.
Figure 15: Flowchart of the SAS algorithm

Step 1
Set model parameters:
Current position of the MB \((x_0, y_0)\), number of directions \(n\).

Step 2
Measure the RSS from all neighbor nodes of the MB:
\(RSS_i(x_0, y_0), i = 0: M\).

Step 3
Choose the nearest unknown position node \(S_k(x_k, y_k)\) from \(M\) neighbor nodes of the MB:
\(RSS_k = \max_{i = 0, \ldots, M} \{RSS_i(x_0, y_0)\}\)

Step 4
\(|\max \{RSS_k\} - RSS_{\text{threshold}}| \leq \delta\)

Step 5
After checking all possible directions, let the MB move in direct, which has the highest growth of the RSS. Then update the current location of the MB.

Step 6
Location of unknown position node \(S_k(x_k, y_k)\) is \((x_0, y_0)\)

Step 7
Know all the node coordinates?

End
4.5.2 Performance analysis of the position location technique in non-Line-of-Sight environment for WSNs

To evaluate the efficiency of my proposed algorithms, I focus on comparing the average location error by my proposed algorithms: SA, SGA, SAS, EPCS, and the algorithm proposed in [14]. The detection capacities of these algorithms are depicted in Figure 16. It can be seen that the average location error and the execution time of these algorithms are in inverse variation. Therefore, they should be chosen depending on the specific application requirements.

Figure 16: The average location error versus the velocity of the MB
5 Conclusion of theses and applications of the results

I have introduced new methods and algorithms, which:

⋆ achieve exact mathematical formulation of objective functions for routing solutions in WSNs;

⋆ have a survey and a complete quantitative comparison of numerical methods for energy-efficient and reliable routing protocols in WSNs;

⋆ achieve energy-efficient and reliable routing protocols in WSNs;

⋆ are proved to be highly flexible even under fast changing environments;

⋆ have low computation complexity of the proposed algorithms and they can be executed in polynomial order of time;

⋆ reduce the runtime significantly by executing the multi-carrier selection in parallel manners.

Furthermore, I managed to make a number of other contributions to the solution of each problem. In case of resource management and packet scheduling, the proposed scheduling algorithm achieves a new efficient method to transmit data with low energy consumption, and with high transmission reliability by developing a smart scheduler. In maximizing the
network lifetime in MWSNs, I developed a new method for gathering data in short time with small energy consumption. In improving the QoS routing for WSNs, I developed a routing algorithm which can optimize multi-path routing in WSNs and improves the energy efficiency under a reliability constraint. In outlier detection problem, I have proven that my proposed algorithm can be used to detect the network violations. I also developed Simulated Annealing method for sensor node localization, which has low average location error and execution time.

Considering the above results, I have achieved the aims of the dissertation. Finally, in each case, I have implemented a proof of concept and have run extension simulations on both synthetic and real-world data.

My proposed methods and algorithms may be used in scheduling of computational resources, monitoring WSN applications, detecting network violations, tracking applications, robotic strategies, etc. The applications of these are summarized in Table 3.

<table>
<thead>
<tr>
<th>Table 3: Summary of my theses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A.1. Field:</strong> Resource management and packet scheduling</td>
</tr>
<tr>
<td><strong>A.2. Performance</strong></td>
</tr>
<tr>
<td><strong>Characteristic</strong></td>
</tr>
<tr>
<td>Improvement in system cost (%)</td>
</tr>
<tr>
<td>System reliability (with $M = 29$)</td>
</tr>
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</table>

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### A.3. Applications

<table>
<thead>
<tr>
<th>WSNs</th>
<th>Other areas</th>
</tr>
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<tbody>
<tr>
<td>Packet scheduling, LAN protocols</td>
<td>Telecommunication, Resources management, the resource may include in human resource, financial resources, human skills, production resources, or some natural resources.</td>
</tr>
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</table>

### B.1. Field: Maximizing the network lifetime in MSWNs

#### B.2. Performance

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Method</th>
<th>Achieved value</th>
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<tbody>
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<td>Network lifetime</td>
<td>LEACH</td>
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<tr>
<td></td>
<td>Improved LEACH</td>
<td>1454</td>
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<td></td>
<td>CHE</td>
<td>1631</td>
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### B.3. Applications

<table>
<thead>
<tr>
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<th>Other areas</th>
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<tr>
<td>Cluster head election in WSNs, efficient mobility technology in WSNs</td>
<td>Optimize movement schedule, Robotic, Traveling salesman problem applications</td>
</tr>
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</table>

### C.1. Field: Routing protocol for WSNs

#### C.2. Performance

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Method</th>
<th>Achieved value</th>
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<table>
<thead>
<tr>
<th>Table 3 – Continued from previous page</th>
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<tbody>
<tr>
<td>Network lifetime</td>
</tr>
<tr>
<td>Existing method</td>
</tr>
<tr>
<td>Novel</td>
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<tr>
<td>Network reliability</td>
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<tr>
<td>Existing method</td>
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<td>Novel</td>
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C.3. Applications

WSNs

Efficient routing technique for WSN

Other areas

Quality of Service in telecommunication networks

D.1. Field: Outlier detection in WSNs data

D.2. Performance

<table>
<thead>
<tr>
<th>Characteristic</th>
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<th>Achieved value</th>
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<tbody>
<tr>
<td>Identification rate</td>
<td>Existing method</td>
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</table>

D.3. Applications

WSNs

Detecting outlier values and events in sensor readings

Other areas

Detecting network violations, outlier detection in some realistic monitor applications

E.1. Field: Position location technique

E.2. Performance

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Method</th>
<th>Achieved value</th>
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<tbody>
<tr>
<td>Average location error</td>
<td>Existing method</td>
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<table>
<thead>
<tr>
<th>Average execution time</th>
<th>SGA</th>
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<td></td>
<td>SA</td>
<td>0.41</td>
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<tr>
<td>Existing method</td>
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<td>SGA</td>
<td>8.8</td>
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<tr>
<td>SA</td>
<td>17.8</td>
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### E.3. Applications

**WSNs**
- Tracking sensor location, find the best routing for WSNs based on location of nodes.

**Other areas**
- Traffic tracking applications, robotic strategies.
References


Other own publications


References


