KSII TRANSACTIONS ON INTERNET AND INFORMATION SYSTEMS VOL. 7, NO. 7, Jul. 2013 1585
Copyright ⓒ 2013 KSII

RRSEB: A Reliable Routing Scheme For Energy-Balancing Using A Self-Adaptive Method In Wireless Sensor Networks

Ahmed M. Shamsan Saleh[1,2]*, Borhanuddin Mohd. Ali[2], Hafizal Mohamad[1], Mohd Fadlee A. Rasid[2] and Alyani Ismail[2]
[1] Wireless Communications Cluster, MIMOS Berhad, Technology Park Malaysia, 57000 Kuala Lumpur, Malaysia
[2] Department of Computer and Communication Systems Engineering, Universiti Putra Malaysia,
43400 UPM Serdang, Selangor, Malaysia
[e-mail:{borhan, fadlee, alyani}@eng.upm.edu.my; hafizal.mohamad@mimos.my]
*Corresponding author: Ahmed M. Shamsan Saleh, [e-mail: ah_almshreqy@yahoo.com]

Received April 8, 2013; revised June 13, 2013; accepted July 5, 2013; published July 5, 2013

Abstract

Over recent years, enormous amounts of research in wireless sensor networks (WSNs) have been conducted, due to its multifarious applications such as in environmental monitoring, object tracking, disaster management, manufacturing, monitoring and control. In some of WSN applications dependent the energy-efficient and link reliability are demanded. Hence, this paper presents a routing protocol that considers these two criteria. We propose a new mechanism called Reliable Routing Scheme for Energy-Balanced (RRSEB) to reduce the packets dropped during the data communications. It is based on Swarm Intelligence (SI) using the Ant Colony Optimization (ACO) method. The RRSEB is a self-adaptive method to ensure the high routing reliability in WSNs, if the failures occur due to the movement of the sensor nodes or sensor node's energy depletion. This is done by introducing a new method to create alternative paths together with the data routing obtained during the path discovery stage. The goal of this operation is to update and offer new routing information in order to construct the multiple paths resulting in an increased reliability of the sensor network. From the simulation, we have seen that the proposed method shows better results in terms of packet delivery ratio and energy efficiency.

Keywords: *Reliability, Energy Efficient, Energy Balancing, Link Failure, Swarm Intelligence*

http://dx.doi.org/10.3837/tiis.2013.07.004

1. Introduction

A WSN is a group of sensor nodes (SNs) working in uncontrolled areas and organized into cooperative network [1]. Each node has a processing capability, a radio, one or more sensors, memory and a battery [2]. Since SNs are usually operated by a limited battery power which may not be replaceable once deployed [3], it is therefore vital for the WSN to an extended network lifetime, one of the ways is by ensuring that the sensor network is energy balanced.

SN usually includes four main components: sensing, computing, communication and power supply (**Fig. 1**). The sensing unit normally contains one or more sensors, analog-digital converter (ADC) and digital-analog converter (DAC). The sensors monitor the physical events and produce the analog signals. Then, it converts the signals to digital and passes to the computing unit for further processing. The computing unit in general includes a processor and memory storage which together provide smart control for the node. The communication unit comprises of a short range radio for transmitting and receiving data, which consumes the highest level of energy in the node [4]. The last unit is the power supply which includes the battery that provides power to all other units. Therefore, it is most important to control the battery power in order to maximize the sensor network life time as it is not easy to replace batteries after they have been deployed in the field. Power control is done by adopting techniques at different layers to conserve the energy in this most exhausting unit.

Radio communications unit of sensor nodes incurs high energy costs on the sensor nodes, especially while in active mode (transmit and receive). In fact, the energy consumed in the sleep and idle modes are so much smaller compared to transmit and receive modes [5]. Hence, this study focusing on the energy consumption at the communication unit during the transmitting and receiving state.

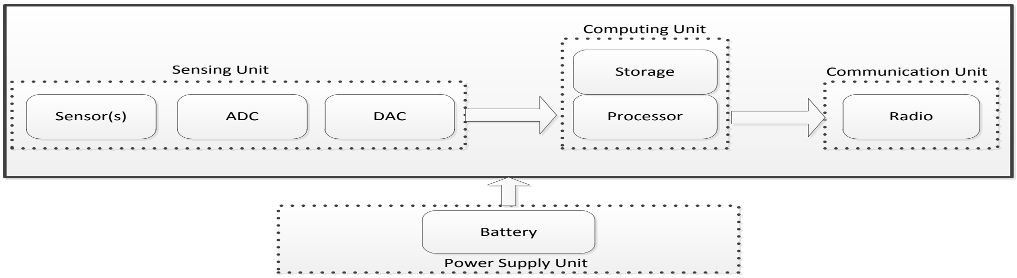

Fig. 1. Block Diagram of a Typical Sensor Node

In this paper, we proposes the RRSEB scheme which is a self-adaptive method to ensure a high routing reliability in wireless sensor networks in case of occurrence of connection failures caused by movement of sensor nodes or depletion of sensor node energy. This is done by ensuring that how reliable the captured data can be reported to the sink-node; hence the proposed mechanism is made to be adaptive to reduce packets drop. The main goal of RRSEB is to update and offer new routing information by constructing the multi-paths in order to increase the reliability of the system. Hence, the proposed method contains three major functions. The first function is the dissemination of pheromone function which employs current routing data to explore the potential paths by adapting the self-sustaining process. The second function is related to the ant gathering function that examines and updates the new routes using the self-learning process. The last function is the detection and correction function which handles the failures as follows: the first operation is to detect the errors, and the next one is to specify the type of errors and finally, to suggest suitable corrective actions for these errors.

The rest of this paper organized as follows: Section 2 reviews some of the related work, Section 3 describes the system models used in the proposed protocol, while Section 4 introduces in detail the design and the main operations of our RRSEB protocol, Section 5 presents the performance evaluation of the proposed method. The last section summarizes our work.

2. Literature Review

In this section, a background review of the energy awareness routing protocols in wireless sensor networks are presented. The majority of routing protocols for WSNs aim at decreasing the energy usage of sensor nodes by either explicitly taking energy into account during the route selection or by optimizing some metrics, such as minimizing the energy consumed per packet, reducing the cost / packet ratio, or minimizing the high energy depletion of any one sensor.

Many energy efficiency MAC and routing protocols have been presented to reduce energy usage in WSNs using sleep mode to turn off some parts of SN, to saving energy, during idle mode. In [6], the authors presented dynamic awakening method, that makes sleep time longer for SNs by estimated the idle phase for each node during sensing and transmission mode. Hence, the SNs within the desired object range switch to active mode on time and serve like sensing candidates. Their dynamic scheme improves the energy efficiency and reduced the total consuming energy in the sensor network. The authors in [7], proposed a wake-up MAC scheduling which switches the nodes from active to sleeping mode whenever required. In [8, 9], a new network layer energy efficient routing strategies are proposed, where sleep state of some nodes were considered as well. Below we reviewed some of the energy aware routing works from two angle Ant Colony Optimization ACO-based and classical optimization based.

ACO is possibly the best studied field in swarm intelligence (SI) algorithms. Usually, SI is the basis of studying the collective behavior of distributed, self-configuring principles such as ant colonies [10]. The main rules of the ant systems are generally performed locally from a population of ant agents interacting with each other and their environment. These agents are capable of solving complex tasks with simple resources. There is only indirect communication between agents via their surroundings adjustment, for example, pheromone trail used to forage efficiently. Ants first work randomly throughout the foraging process, then it follows the same path to the nest which is indicated by the pheromone. During the return journey more pheromone trace is deposited to show the direction of destination by tracking this trail on the shortest route. Ants communicate via changes in the ambient -pheromone trace- this process is called stigmergy, the detail of ACO algorithm can be found in [11].

In [12], the Energy Efficient Ant-Based Routing (EEABR) is designed to extend the life time of WSN by decreasing communication overhead in the discovery phase. This is attained by way of two factors-- energy and hop count when updating the pheromone. In addition, they use a fixed ant size to construct energy efficiency routes. Ants are generated proactively in EEABR at regular intervals and unicasted to the next hop SNs that is selected by a probabilistic rule. Furthermore, the EEABR is a weak in terms of the scalability and reliability.

In [13], the authors first proposed a routing based-on centralizing offline ant colony system to solve the Steiner tree problem. Later they presented a distributing online-based for data centric routing in sensor networks. The WSN is presented as a weighted graph where a weight-cost of an edge is the Euclidean distance of the connected SNs. The object is then to gain a Steiner tree of minimum cost when forwarding packets to the sink. The authors built their method using a unique base-station.

Many-to-One Improved Ant Routing (MO-IAR) in [14], proposed an ant-based protocol that is designed for upstream routing many-to-one sensing packets. The routing algorithm is linked with a congestion control scheme that helps to alleviate the collision. The protocol is divided into two stages; during the first stage, it finds the shortest route between any SN and the destination while in the second stage it exploits the shortest route to prevent the congestion and minimize packet loss. The protocol assumes that the location of each SN, the target, and their neighbors are known.

A prominent energy-efficient algorithm for clustered networks is the Low Energy Adaptive Clustering Hierarchy (LEACH) [15]. LEACH uses data aggregation techniques and a cluster head selected in a random way. It is a routing model based on hierarchical topology and energy efficiency. The authors in [16], proposed the Routing based on Energy–Temperature Transformation (RETT-gen), which is a modification of the LEACH protocol, taking into consideration residual energies of the sensors in routing decisions. They disseminate equally the energy load over all SNs in networks thereby extending the network lifetime. However, the persistent problem in this protocol and other clustering protocols is that the cluster formation process as well as the probabilistic cluster-head selection incur high overheads and complexity.

The power-efficient gathering in sensor information systems (PEGASIS) [17], introduces a new factor delay-energy, which concurrently decreases delay and energy cost. PEGASIS is similar to LEACH but uses lower energy per round. It creates a chain such that if a sensor has data to send to the sink, it goes through the leader sensor, which is chosen randomly every round. However, one of the limiting factors of PEGASIS is that every sensor has to aggregate data such that packet transmission is minimized. Moreover, the protocol requires the global information of the network and uses greedy method before the chain formation can be done, which requires data packet traversal through many sensor nodes.

The work in [18], proposed a distributed energy balanced routing (DEBR) protocol, which decentralizes the data traffic in the network in a way that prolongs the lifetime of the network. The algorithm made a tradeoff between packet delay and energy. Despite the applicability of the algorithm in many WSN scenarios, it assumes that each SN is within the direct communication range of the sink, which is not true for multi-hop routing.

3. The System Models of RRSEB Protocol

As has been highlighted before, WSNs have strict energy requirements and dynamic changes. Hence, the routing protocols should take into consideration these constraints to develop algorithms that have the capability to distribute the load traffic, in order to avoid the extra loading of nodes at the same route and react to any failures occurrence during the data routing. As a result, the life time of the sensor nodes can be extended and packets drop reduced, while the energy balancing and energy efficiency will be satisfied at the same time.

Thus, this section gives details about the models used in this paper to design and implement the proposed distributed routing protocol (RRSEB), involving energy consumption, lifetime, traffic generator, ants, pheromone tables, nodes, and network models.

3.1 Energy Consumption Model

Energy consumption in WSN is mainly attributed to the radio system in active mode. In fact, the energy consumed in the sleep and idle modes are very small compared to transmit and receive modes. Let sensor node x has N bits of packets to transmit or receive during active mode (per unit time). Accordingly, the total energy consumption for x can be calculated as:

$$\boldsymbol{ToEnC(x) = EnC^{Tx}(x) + EnC^{Rx}(x)} \tag{1}$$

where the $EnC^{Tx}(x) and\ EnC^{Rx}(x)$ are the circuit energy consumption for the node x during the transmission and receiving states respectively. The energy consumed due to transmission $EnC^{Tx}(x)$ is given by

$$\boldsymbol{EnC^{Tx}(x) = EnC^{elecT} + EnC^{amp}} \tag{2}$$

where EnC^{elecT} is the electronic circuit energy consumed due to the transmitter, which is calculated as:

$$\boldsymbol{EnC^{elecT} = EnC^{mx} + EnC^{Sny} + EnC^{filt} + EnC^{dac}} \tag{3}$$

where EnC^{mx} ,EnC^{Sny},EnC^{filt} $and\ EnC^{dac}$ are the energy consumption of the mixer, frequency synthesizer, filter and digital to analog converter respectively, and EnC^{amp}, the energy consumed by the power amplifier.

In the same manner, the energy consumption in the receiving state $EnC^{Rx}(x)$ is given by

$$\boldsymbol{EnC^{Rx}(x) = EnC^{elecR}} \tag{4}$$

where EnC^{elecR} is the electronic circuit energy consumption at receiver and calculated as:

$$\boldsymbol{EnC^{elecR} = EnC^{mx} + EnC^{Sny} + EnC^{filt} + EnC^{lna} + EnC^{ifa} + EnC^{adc}} \tag{5}$$

where EnC^{lna},$EnC^{ifa} and\ EnC^{adc}$ are the energy consumption of the low noise amplifier, the intermediate frequency amplifier and the analog to digital converter respectively.

Based on equations (1), (2) and (4), the energy consumption per packet bits $EnC_{Pkt}(x)$ is given by

$$\boldsymbol{EnC_{Pkt}(x) = ToEnC(x)/N} \tag{6}$$

3.2 Lifetime Model

The network lifetime in a sensor network depends on many factors, including the energy model, frequency coverage, message size, and aggregation schemes [19]. Therefore, WSN has to select suitable components that allow the routing protocol to extend sensor network lifetime. Accordingly, this paper measures the lifetime based on the energy consumption model. Hence, the lifetime of the network is defined as the time spent from deployment until the first sensor or part of sensors becomes unable to transmit packets to its neighbor because of depleted energy.

Therefore, the lifetime of sensor node x based on equation (6) is given by

$$\boldsymbol{LT(x) = \frac{E_{init}}{EnC_{Pkt}(x)}} \tag{7}$$

where E_{init} is the initial energy of the sensor node.

This means that the lifetime of the greediest node in the network must be maximized in order to improve the network lifetime. This problem can be represented by the following minimization function:

$$\boldsymbol{MaxLT(x) = min(max(EnC_{Pkt}(x)))\ \ x \in V} \tag{8}$$

3.3 Ant Model

In RRSEB protocol the ant packets classified based on the operation that used during the routing process either a request Ant-Forward (F-ANT) or a reply Ant-Backward (B-ANT). During the path discovery steps where the on-demand (reactive) mechanism is employed, we used the reactive Ant-Forward (F-ANT$_r$) and reactive Ant-Backward (B-ANT$_r$). Whereas in path recovery steps that employed the proactive mechanism, we used a proactive Ant-Forward (F-ANT$_p$) and a proactive Ant-Backward (B-ANT$_p$). Furthermore, in this phase also the fixed Ant-Forward (F-ANT$_f$) and the fixed Ant-Backward (B-ANT$_f$) are used during the correction of failures.

3.4 Pheromone Tables Model

In RRSEB protocol, each sensor node *x* maintains a pheromone table (routing table) R$_x$. Each entry in the table R^{z}_{xy} includes the information of the path from sensor *x* to the base station (sink) *z* through its neighbor y. The value of both pheromone are referred to as real and non-real, whereby the real pheromone indicates the path quality from sensor *x* to the base station (sink) *z* through its neighbor *y*, gathered by Ant-Forward (F-ANT) and updated by Ant-Backward (B-ANT). The non-real pheromone which indicates the alternative path quality from sensor *x* to the base station (sink) *z* through its neighbor, will be obtained during path recovery stage by using the reinforcement learning mechanism. Therefore, this table keeps the data routing up-to-date using the pheromone trail collected by F-ANT and reinforced by B-ANT, which tracks back the same route constructed by F-ANT.

4. The Design of RRSEB Protocol

In this paper, RRSEB will use both on-demand and proactive mechanisms, where the on-demand process will trigger when the sensor node has a data packet to be sent to the sink whereas no information is available in its routing table. In contrast, the proactive starts during the communication period to update the information of WSN and use it later during route maintenance steps. In addition, this operation provides multiple choices of routes to respond with any malfunctioning in WSN during the failure links or fast run-out of sensor's battery.

Fig. 2 presents more details of the RRSEB scheme including summarizing the main components and illustrating the cooperation between its main operations. The first part is the discovery phase which finds the routes from the source node to the sink node using the reactive mechanism. The second part is the recovery phase comprises of two operations namely the dissemination of pheromone and the ant gathering operation using partially proactive mechanism. This diagram also shows the objectives of these processes and presents the tools and control packets used. Finally, it also explains the error detection and correction phases with the respective tools and their objectives. More details about all these processes are given in subsections 4.1 and 4.2.

The objective of these operations is to discover alternative routes, and to fix the existing path by sending control packets. After creating the path in discovery phase, during the session of communicating and sending the data packets between the sensors, the RRSEB begins to search for new available paths and update the information of the current routes to increase its reliability and detect failures. Accordingly, the RRSEB starts to broadcast the pheromone data which was collected by discovery operation using the dissemination of pheromone operation, in order to extract new pheromone values. This new pheromone values is named hereinafter "non-real pheromone". Therefore, in this operation, the sensor searches for new paths using its own data; this is a self-sustaining behavior which is very useful and more reliable for adapting to any dynamic changes inside the sensor networks.

The self-sustaining behavior exploits the result from a real pheromone, that was collected from the discovery phase, to use it proactively during the sender communication session, and it broadcasts the proactive forward ants (F-ANT$_p$) to all its neighbors and thus moving them forward up to the sink. These F-ANT$_p$ build the route randomly and select the next hop by considering the real and non-real pheromones together. Thus, the ants will track only the paths that come out from the broadcasting of the pheromone data, which means the paths will be established by the proactive ants. More details about this operation are discussed in sub-section 4.2.2.

When the F-ANT$_p$ arrive at the sink node, they are converted into B-ANT$_p$ and return back to the sender node, in the same way as the B-ANT$_r$ in path discovery, thus following the real pheromone only. In this manner, RRSEB uses what we call a self-learning behavior because at the first time, the F-ANT$_p$ ants start the search operation towards the sink with the non-real pheromone, and afterward when they comfortably reach the sink node, they use the real pheromone information with the B-ANT$_p$ ants. More detailed discussion about this is presented in sub-section 4.2.3. In this manner, we can conclude that self-sustaining behavior broadcasts the pheromone information using F-ANT$_p$ ants to propose the new routes, after which, a self-learning behavior uses B-ANT$_p$ ants to verify these routes. Based on these techniques, the RRSEB grants reliability against any failure occurring in the sensor networks.

Up to this point, when the sensor finds the failure, it looks inside its pheromone table to mark the paths associated with it, and checks it for other potential paths available to the sink. Accordingly, the sensor informs its neighbors about the modification in its routing table. If the data messages fail to transmit, the sensor starts the maintenance phase by dispatching the Forwarded-Ant (F-ANT$_f$) to fix the existing path. When it reaches the target of this data, it is converted into the B-ANT$_f$ back to the same sender which is almost similar to the manner in which the F-ANT$_r$ and B-ANT$_r$ are used in the discovery process. Further details of these operations are provided in sub-sections 4.2.4, 4.2.5 and 4.2.6.

4.1 Path Discovery Steps

When the node senses data to forward to the base-station (sink), it will check inside its routing table to verify existing route to the sink. If no data is available, the sender sensor will start to broadcast F-ANT$_r$ to find out the route to the sink; otherwise, it will send unicast F-ANT$_r$ using the pheromone information and quality function of both path and hop to select the next hop from x to y toward sink z. It uses the ant agent probability Pr_{xy}^{z} given as follows:

$$\boldsymbol{Pr_{xy}^{z}} = \frac{(\boldsymbol{P_x^y})^{\boldsymbol{\beta}}}{\sum_{y\in \boldsymbol{N_x^z}} (\boldsymbol{P_x^y})^{\boldsymbol{\beta}}} \tag{9}$$

where P_x^y is the pheromone trail value of the link (x,y) and β is the weight factor of the pheromone trail.

During the receiving F-ANT$_r$ message from the sensor node x to the sink z through y, it starts assessing the function quality of the ant route, $F(ph)_{xyz}^{z}$ as follows:

$$\boldsymbol{F(ph)_{xyz}^{z}} = \boldsymbol{F(ph)_{xyz}^{y}} + \boldsymbol{EnC_{xy}^{Tx}/F(hp)_{xy}} \tag{10}$$

where $F(ph)_{xyz}^{y}$ is the quality of the route from the sender of F-ANT$_r$ at the intermediate sensor y, EnC_{xy}^{Tx} is the consumed energy to forward the data from x to y and $F(hp)_{xy}$ is the function to assess the quality between neighbor sensors x and y, and is given as:

$$\boldsymbol{F(hp)_{xy}} = \boldsymbol{e^{y}} * \boldsymbol{e_{min}^{y}} * \left(\frac{\boldsymbol{e_{av}^{y}} + \boldsymbol{e^{y}}}{\boldsymbol{e_{nw}^{y}} * \boldsymbol{h^{y}}}\right) \tag{11}$$

where e^{y} is the current residual energy of sensor y, e_{min}^{y} is minimum residual energy of sensors visited by F-ANT$_r$ given as Min$[e_{min}^{x}, e^{y}]$, e_{av}^{y} is the average residual energy of the route from sender x until the current sensor y, h^{y} is path length up to y and e_{nw}^{y} is the total average of the whole network residual energies which is computed as the initial energy of the sensor at the first time and later updated with F-ANT$_r$ and B-ANT$_r$ using:

$$\boldsymbol{e_{nw}^{y} = \alpha e_{nw}^{x} + (1-\alpha) e_{nw}^{y}} \tag{12}$$

where α is the parameter for updating the ratio of predicted and received network average energy.

Consequently, based on the hop function $F(hp)_{xy}$, our model satisfies the balancing of energy consumption that reduces sensor's energy usage in the path and prolong the network life span. This is done by preventing the frequent usage of sensor nodes based on a minimum energy level used here. Hence, the sensor nodes with maximum residual energy will take the role of transmitting the data, and the paths with high average residual energy will get more opportunities to route the data to the sink.

In addition, the results of hop quality function will be applied to eq. (10) to measure the whole ant tour route from sender sensor node to sink. In this case the higher value associated with this route function will be given less path average, which is the better path to be chosen. As a result, the protocol will use this to update the pheromone trail P_x^y at the pheromone table as follows:

$$\boldsymbol{P_x^y = (1-\omega) P_x^y + \Delta P_{xyz}^{z}} \tag{13}$$

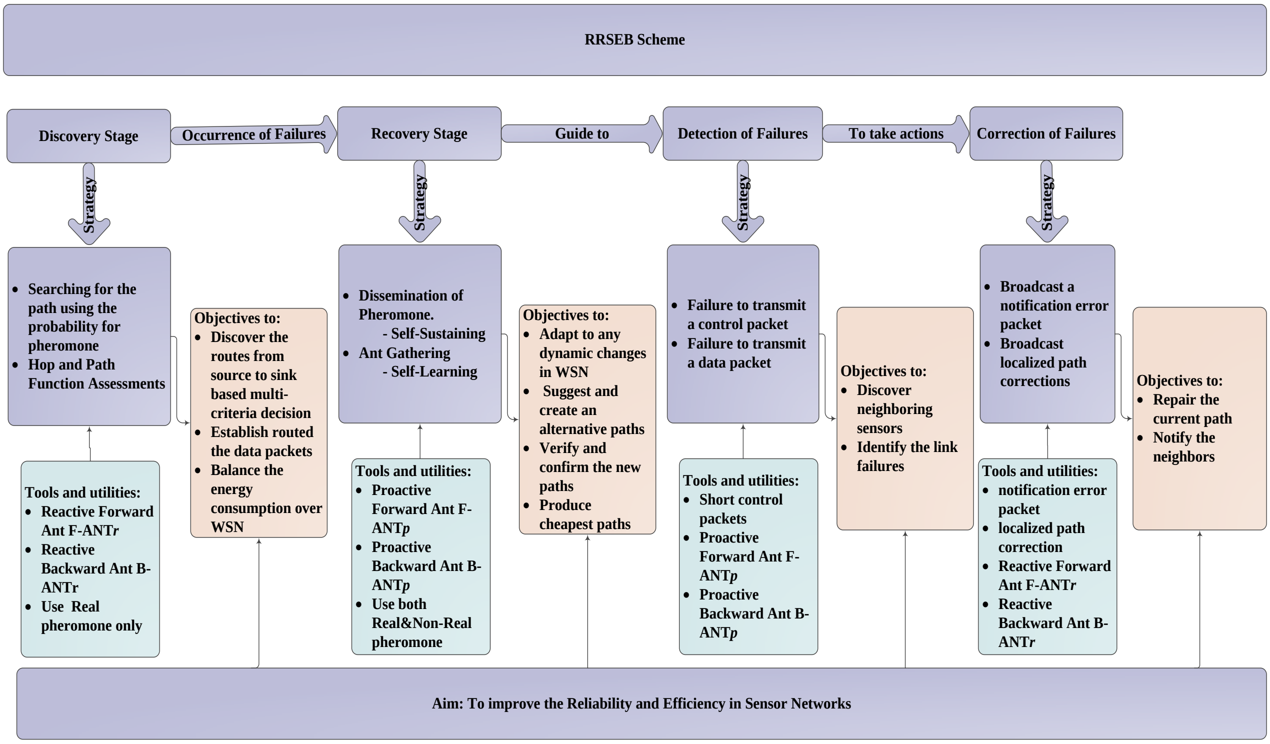

Fig. 2. The Main Components of RRSEB and their Cooperations

where ω is the parameter to control the decay of the pheromone during the searching process since last updated and ΔP_{xyz}^{z} is the increasing value of the ant deposit trail during the journey from the sender node to the sink. This is given as the inverse of function quality of the route from source sensor to the sink:

$$\boldsymbol{\Delta P_{xyz}^{z} = 1/F(ph)_{xyz}^{z}} \tag{14}$$

Therefore, the route with better quality that have both highest value of minimum residual energy and average route energy will get the higher pheromone trail. In this way the route with best path quality will reinforce and get a better chance to be chosen.

Up to this point each sensor may receive multiple copies of the same F-ANT$_r$ therefore it removes all duplicate copies that arrive after the first F-ANT$_r$. Additionally, the sensor looks for the sink address carried by the F-ANT$_r$; if it is different from the current one it will broadcast the F-ANT$_r$ and follow the same procedure as before, otherwise it will convert the F-ANT$_r$ to B-ANT$_r$.

When the sink node receives the F-ANT$_r$ it will generate B-ANT$_r$ to begin the route reply by using the unicast operation using the same path used by the F-ANT$_r$ forwarded to the sender node. During the route reply stage using B-ANT$_r$, each sensor that receives the ant updates its routing table using equation (13). When B-ANT$_r$ reaches the final target sensor -the sensor generates F-ANT$_r$ - the process of searching path finishes and the ant is removed. Hence, by applying this technique for several iterations the sensor will be able to find the optimal route to transmit the data to sink.

4.2 Path Recovery Steps

In this method, when the source transmits data to the sink within a period of this session it will start sending F-ANT$_p$ to explore and update the information about the current routes. This process periodically checks the changes in the WSN caused by link failure, either by movement of the sensors or the depletion of sensor nodes energy in the available path. This process involves the same concept of path searching; it checks the energy level to compute path quality function and update the pheromone information to start building new alternative routes. This is obtained by reinforcement learning scheme to update the pheromone table, replacing the maximum value of the pheromone trace based on the multi-criteria function qualities of both hop and path, which frequently monitor the energy level of the sensors in relaying the data. The advantages is that, this strategy will avoid routing the data packet using the same path all the time and prevent the sensor nodes from being drained very quickly, thus resulting in an extended network life time.

4.2.1 The Path Recovery Schematic

The RRSEB path recovery operations use the proactive route method to create alternative paths together with the pheromone knowledge obtained through the path discovery stage. The goal of these operations is to update and offer new routing information by constructing the multi-paths from the sender sensor to the sink in order to increase its reliability. The proactive scheme of the path recovery used in RRSEB consists of two main operations namely, the dissemination of pheromone and the ant gathering operation. Dissemination of pheromone is designed to distribute information about the current pheromone on the sensor nodes using control packets at regular intervals. And the ant gathering operation uses the proactive method to monitor and update the pheromone data with F-ANT$_p$ based on the real or non-real information. This operation is only associated to each unique session which begins and finishes with it. However, the dissemination of pheromone is performed by all sensors during their life span. The path recovery schematic is described in **Fig. 3** along with the outline of the three main operations, their procedural steps and the relationship among these steps. It also explains the cooperation among the three operations. All details about the path recovery processes are described in the following sub-sections.

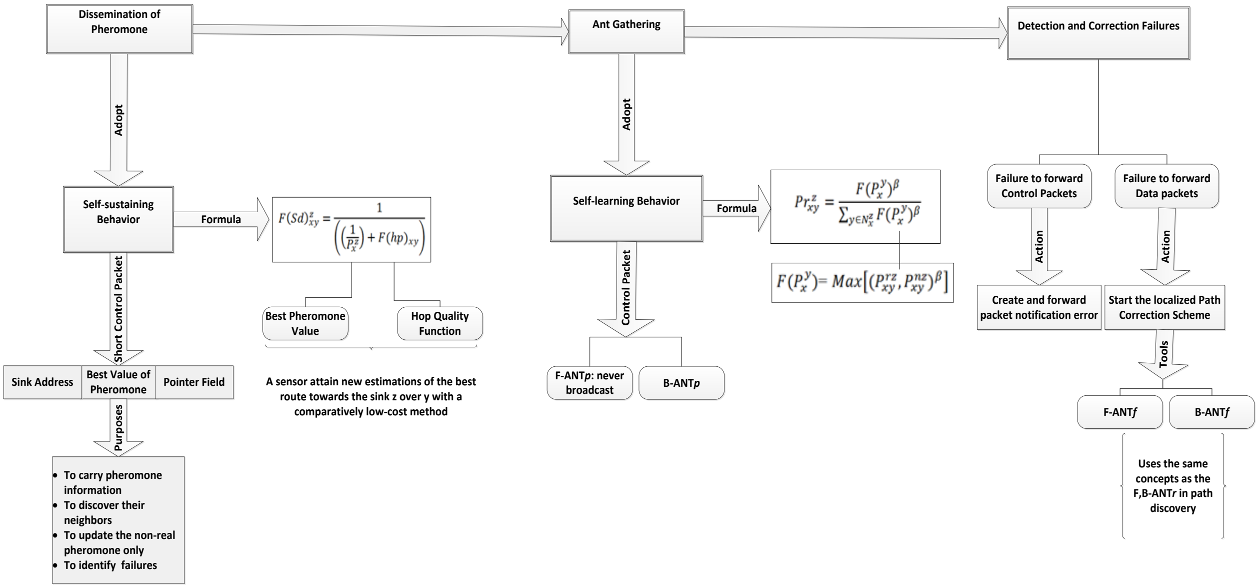

Fig. 3. The Path Recovery Schematic

4.2.2 The Dissemination of Pheromone Operation

The path discovery process uses the reactive ants which lead to the availability of a unique path specified by the sender node of a current session to sink, and indicated by the real pheromone values inside the sensor's routing table. In addition, each sink's neighbors have a one hop link to it which is also indicated by real pheromone values. This is because sensors' neighbors are concerned about the existence of one another. The goal of this operation is to disseminate the pheromone data and as a result of this, the route of pheromone, marking the direction to the sink becomes defined in the WSN. This dissemination process that distributes the pheromone information out is more analogous to the operation of the actual ants in reality which permit far-away ants to benefit and track the disseminated pheromone.

The dissemination of pheromone operation utilizes a self-sustaining behavior to perform sending of short control packets periodically via all sensors in WSN during the sensors' life span. These packets aim to enable the sensors to discover their neighboring sensors and identify the failure when it happens, and to carry the pheromone information. When broadcasting these packets, it includes some routing information such as sink address, best value of a pheromone offer to sink and the pointer field as shown in **Fig. 4**.

Sink Address	**Best Value of Pheromone**	**Pointer Field**

Fig. 4. Frame Structure of Disseminated Control Packets

In that way, the value of the best pheromone is chosen according to real or non-real pheromone linked to the sink node inside the sender routing table. The pointer field points out if the pheromone value is real or non-real. Based on this, the RRSEB method chooses the energy-balanced path that satisfies the quality of the system performance. This is done by selecting the best path having the highest residual energies either indicated by the real or non-real pheromone with the high reliable technique, which allows it to construct multi-routes towards sink node, thus, reserving it as a backup and restoring it when the link failures occur during the communication session.

This means that a sensor neighbor y receives this packet from the sender node x to travel to the sink z, and it infers from this packet the better path from x to z over an intermediate node y by applying the self-sustaining data as follows: it adds the best pheromone value P_x^z from the sender to the sink broadcasted with a packet with the assessment of the local function quality hop $F(hp)_{xy}$ between two neighboring sensors x and y which is described in equation (11). Calculating the self-sustaining in the following new equation:

$$F(S_{sus})_{xy}^{z} = \frac{1}{\left(\left(\frac{1}{P_x^z}\right) + F(hp)_{xy}\right)} \tag{15}$$

where the $F(S_{sus})_{xy}^{z}$ value represents what the self-sustaining pheromone value. It is generated from two inverted operations; the first one is required to change the best value P_x^z to a quality value in order to add it to the quality hop function value $F(hp)_{xy}$ and the second inverted operation is to change the summation once more to the best value.

With $F(S_{sus})_{xy}^{z}$, the sensor x attains new estimation of the best route towards the sink z over y within a comparatively low-cost method.

As previously mentioned, the routing table of the sensor node x has both pheromone values (real & non-real) for the path towards sink z through the intermediate sensor y. In this way, only the non-real pheromone updated by the self-sustaining pheromone $F(S_{sus})_{xy}^{z}$ - replaces the value of the non-real by $F(S_{sus})_{xy}^{z}$-. Hence, self-sustaining pheromone is kept separately from the real one, which is the output of the ant gathering operation that is considered as the most reliable pheromone.

The purpose of holding both pheromones; real and non-real separately is to distinguish between their usages. Whereas the former is used in a direct way to forward the data packets when selecting the next-hop, the latter is used to forward the F-ANT$_p$ ants to the sink node during the ant gathering operation. More details are provided in sub-section 4.2.3. Once the F-ANT$_p$ arrives at the sink, they change into B-ANT$_p$ that are returned back again dropping only the real pheromone, which is sequentially employed to route the data messages. Therefore, a self-sustaining pheromone affects the data transmission indirectly. Based on this, it can be concluded that the self-sustaining pheromone obtained through the dissemination pheromone process gives suggestions for the potential paths, and then these paths are investigated and confirmed in the ant gathering process with self-learning using F-ANT$_p$ and B-ANT$_p$ ants.

With this mechanism, RRSEB confirms that there is a reliable path for sensor x to sink z via sensor y, because the presence of real pheromone shows that this path is previously gathered by ants. Furthermore, RRSEB identifies that a self-sustaining pheromone $F(S_{sus})_{xy}^{z}$ reflects the information of this reliable path that is available for the next-hop y, because it was based-on the P_x^z value which reflects the real pheromone offered by x towards z. Consequently, we could say that self-sustaining pheromone is one way for updating the routing information of this particular path. Therefore, we can use it for updating the real pheromone, which has now sufficient reliability for replacing it directly. In this manner, the pheromone of the existing routes stays up to date.

4.2.3 The Ant Gathering Operation

The ant gathering operation is one of the major components of RRSEB method. It is triggered at the sender sensor when the data starts to be accepted by the sink-node with an ongoing session and it proceeds until the end of the session. The goal of this operation is to collect the routing information for the current sessions. Based on this, the F-ANT$_p$ ants produce and track either the real pheromone which is resulted from the prior ants, or the non-real one coming out from the dissemination pheromone operation as previously explained. While the first one guides the ants to renew the best-quality value of the available paths, the second one enables those ants to explore new paths derived from the suggestions offered throughout the dissemination pheromone operation. In this manner, the unique path that is created during the path discovery phase will increase to multi-paths towards the sink with a low-cost procedure. Hence, the RRSEB produces cheap and more reliable paths, since it uses the self-sustaining way to broadcast the pheromone information, collected by the reactive ants in the discovery stage via an efficient way. Afterward, it uses the proactive ants to create the alternative paths to deal with any link faults via the highly reliable way.

In the ant gathering process, within a session of the current communication, the sender regularly broadcast the F-ANT$_p$ to the sink node. Forwarding the F-ANT$_p$ is limited to the good quality of the existing non-real pheromone value which means that if the quality of the non-real value is more significant than the real pheromone, the F-ANT$_p$ can dispatch. The objective of the F-ANT$_p$ is to discover a path to the sink and to keep the list of all the sensors being visited during its journey. For this reason, the route decision for selecting the sensor y as a next-hop for any intermediate sensor x towards the sink node z is calculated by the probability Pr_{xy}^{z} as follows:

$$\boldsymbol{Pr_{xy}^{z}} = \frac{\boldsymbol{F(P_{xy}^{z})^{\beta}}}{\sum_{y\in N_x^z} \boldsymbol{F(P_{xy}^{z})^{\beta}}} \tag{16}$$

where $F(P_{xy}^{z})$ is the indicator of pheromone trail value that returns the maximum value of real P_{xy}^{rz} or non-real pheromone P_{xy}^{nz} . It is calculated as follows:

$$\boldsymbol{F(P_{xy}^{z})} = \boldsymbol{Max}\left[(\boldsymbol{P_{xy}^{rz}}, \boldsymbol{P_{xy}^{nz}})\right] \tag{17}$$

and β is the weight factor of the pheromone trail which controls the exploration of the ants.

From equations 9 and 16, the difference between F-ANT$_r$ and the F-ANT$_p$ which are used in RRSEB is that the F-ANT$_p$ ants depend on both real and non-real pheromone values during the route decision. Moreover, they also use only the unicast operation so if the sensor receives these ants, and it does not have any routing information about the route to the sink, the sensor will remove it.

Up to this point, if the F-ANT$_p$ ants are received correctly at the sink node, they are changed into backward B-ANT$_p$ ants that follow the same route used by F-ANT$_p$ and update the routing information of all the intermediate sensors in the route up to the sender of these ants. As has been highlighted previously, the F-ANT$_p$ can track either the real or non-real pheromone but the B-ANT$_p$ ants only drop the real pheromone. Thus, the operation of ant gathering is capable of examining the potential non-real pheromone and if the examination is achieved correctly, it will change it to real pheromone which is now ready to be used for transmitting the data packets throughout the confirmed path, and this is what we call a self-learning behavior.

This reliable proposed routing mechanism provides multiple paths for routing the data packets. In addition, it utilizes them for any dynamic changes or faults happening inside the sensor networks. As already mentioned, the proactive-ants in this ant gathering process give the essential control to validate the reliability of the possible paths obtained via the self-sustaining operation of pheromone dissemination.

4.2.4 Detection and Correction of Failures

Based on what has been already highlighted, the proposed RRSEB protocol presents some solutions to deal with the errors happening in the WSN. It uses the proactive mechanism during the recovery phase, thus providing multiple routes that act in a similar way to routing backup probabilities.

This section explains in details how the RRSEB handles the occurrence of failures during forwarding of the packets either in the form of data or control. Hence, if the failure occurs is due to failure of forwarding the control packet, then the sensor in RRSEB starts to broadcast a packet notification error. Details regarding this are provided in sub-section 4.2.5. For the second case, if the failure is due to failure of forwarding the data packet, then the sensor starts local transmission of the Forward-Ant (F-ANT$_f$) to fix the path to the target node through the mechanism which is called a localized path correction as described in further details in sub-section 4.2.6.

As discussed before, the control packets are broadcasted by all the sensors periodically to discover the neighboring sender nodes. If any sensor receives this packet, it assumes that the sender is a neighbor with one hop path. Within this regular period of time, if any neighboring sensor does not receive any packets from the sender, it infers that there is no link between them. Thus, these packets carry out dual functions in this proposed scheme: first, it spreads the pheromone data as explained in pheromone dissemination operation. Secondly, it is utilized for error detection.

4.2.5 Broadcasting the Packet Notification Error

To this end, if the sensor notices a missing connection with any neighbor, it updates its routing table and creates a packet error notification. Accordingly, this sensor verifies if the missing pheromone is the best or just the real value exists for the sink, then it attaches the sink's address with an alternative best-pheromone to the packet error notification. After that, this packet is dispatched to all neighbors. As a result, all sensors which receive this packet update their pheromone tables for the paths going to the sink via that missing sensor by using the new information inside the packet. This means that the neighboring sensors employ the same rule declared in equation (15) which is used for dissemination pheromone operation.

However, if any one of those sensors receiving this packet loses the path to the sink, it starts creating and broadcasting the packet notification error again similarly as the sender sensor did. According to this process, all the sensors finally notify and update their routing tables. For these reasons, the RRSEB offers a high reliability with more efficient techniques to detect, handle and notify failures inside the wireless sensor network.

4.2.6 Localized Path Correction Approach

As mentioned earlier, if the failure occurs due to failure of forwarding of the data packet, and the sensor does not contain any possible routing information about the sink node, the sensor initiates a localized path correction procedure to fix the path rather than broadcasting a packet error notification to the sink node. Therefore, the data message is probably to be still delivered.

By launching the localized path correction procedure, a sensor generates fixed forward ants F-ANT$_f$; and the operations of these ants are almost similar to those of the reactive ants F-ANT$_r$ used in path discovery. The decision of routing the ants is based on the information currently available in the pheromone table. If no information available in the tables the ants are broadcasted.

Otherwise, they are unicasted to the next-hop with the same probability rule used in equation (9). In this method, the number of broadcast F-ANT$_f$ is restricted in order to search for the solution near to the current routes towards the sink, hence, the F-ANT$_f$ ants move far only when being unicasted with the available pheromone.

To this end, when the sink receives the F-ANT$_f$, it is converted into the B-ANT$_f$ ants which track the same routes to the sender which starts the localized path correction operation. Again, the B-ANT$_f$ ants perform with the same concepts of reactive B-ANT$_r$ used in path discovery phase as they update all intermediated sensor's pheromone tables with a real value. After the B-ANT$_f$ ants are received by the sender of F-ANT$_f$, the sender starts now transmitting the data packet to the sink.

5. Performance Evaluation

The results obtained from carrying out several simulation experiments in the current study were examined and evaluated in order to prove the performance of the RRSEB under different WSN conditions. The aim of such experiments is to assess the ability of the proposed method and test its effectiveness.

In the following experiments, the RRSEB increases the reliability and efficiency by detecting and correcting the link's failures and balance the energy usage inside the sensor network. By doing so, the result is that the number of packets being dropped decrease. This enhancement is attributed to the proposed method which uses the dissemination of pheromone and the ant gathering operations that update and offer new routing information. This is done by exploiting the sensor pheromone information in a low-cost way, thus resulting into establishing multi-paths between sender and sink. To evaluate the performance of RRSEB used in this paper, we compare it with the performance of our previous SensorAnt method [20] , under the same conditions. The main difference between SensorAnt and RRSEB are both methods working for different purposes in wireless sensor networks based on the application types. The RRSEB is an improvement of the SensorAnt with a new strategy in the recovery phase but both uses the same mechanism in the discovery phase, only. While both use the reactive method during the discovery phase the RRSEB use the proactive method in the recovery phase to increase the reliability using different equations and novel methods to detect, identify and correct failures which does not considered and published before. The SensorAnt outcome is a unique path between source and destination so when failures happen in WSN it uses on demand mechanism to recover the path, whereas the RRSEB results in multiple paths between source and destination so when failures occur in one path it automatically chooses the best alternative path based on the quality assessment function used in our work. Hence, both schemes are different from each other and they just use the same mechanism in the discovery path. Therefore, based on the application demands we can select the suitable method since each has its own role to play. Therefore, the RRSEB scheme is validated by comparing it with SensorAnt to show the tradeoff between them in wireless sensor network which considered as application dependent. If the concern is on reducing energy consumption to maximize battery lifetime the best choice will be the SensorAnt. But if the concern on reliability and the demand is to reduce packet drops, so the best choice will be RRSEB.

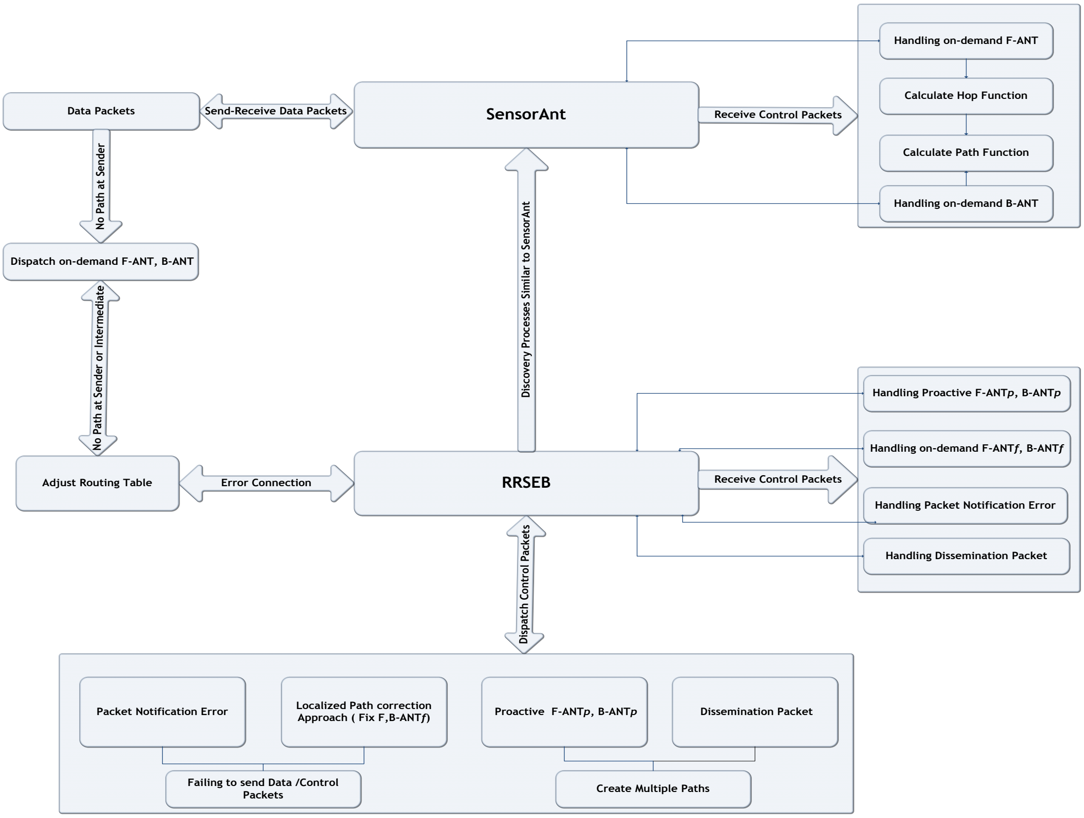

Fig. 5. The Relationship between SensorAnt and RRSEB with their Respective Main Elements

Fig. 5 illustrates the relationship between SensorAnt and RRSEB and its main elements and operations that discussed briefly in the previous paragraph. Moreover, the main function of both schemes can be described as follows: First, the RRSEB operations focus on enhancement of the path recovery process by introducing proactively route mechanism to create alternative paths together with the data routing obtained by path discovery stage. The goal of these operations is to update and offer new routing information in order to construct the multi-paths resulting in an increase of reliability of the system. We introduce two concepts in this scheme called self-sustaining and self-learning. Self-sustaining disseminates information about the current pheromone value on the sensor node, using the packets at regular intervals; the objective of this operation is to give the suggestions of potential routes. Self-learning monitors and updates the routing information during a communication session; the objective of this operation is to validate the routes resulting from the previous operation. Additionally, the RRSEB employs the periodic packets used in self-sustenance to check the presence of neighboring sensors in order to adjust their routing tables when links' failure occurs.

Second, the SensorAnt is a self-optimization scheme for WSN. It is able to utilize and optimize the sensor nodes' resources, especially the batteries, to achieve balanced energy consumption across all sensor nodes. The SensorAnt is adopted to enhance the paths with the best-quality function during the route discovery phase. The assessment of this function depends on multi-criteria metrics such as the minimum residual battery power, hop count, average energy of the route and average energy of the network. The proposed SensorAnt scheme uses nodes with high residual energy to take part in the data packet relaying to the sink, and excludes nodes with low residual energy thereby extending the ability of the SNs to communicate with each other as much as possible. This method also distributes the traffic load of sensor nodes throughout the WSN leading to reduced energy usage and extended network life time.

5.1 Simulation Environment

The proposed RRSEB scheme is simulated by deploying different sensor nodes from 60 to 80 randomly over 600×600 m^2 with flat based topology networks. The other parameters used in the simulation are listed in the **Table 1**.

Table 1. Simulation Setting

Name	Value
Simulation Tool	QualNet V5.0
Channel Frequency	2.4GHz
Traffic	CBR
Packet Size	32 byte
Energy Model	Micaz
Data Rate	250Kbps
Initial Energy	1250 mJoule
α	0.7
β	1
ω	0.8

Performance Metrics Evaluation

The performance metrics discussed in this subsection are energy consumption, energy efficiency, average residual battery power, and packet delivery ratio.

1) **Energy Efficiency:** This is the ratio between total consumed energy over the number of packets received by the sink-node. Which is calculated as follows:

$$\boldsymbol{Energy\ Efficiency} = \frac{\sum_{i=1}^{n} \boldsymbol{ToEnC(i)}}{\boldsymbol{ToPck_{snk}}} \tag{18}$$

where the *n* represents the number of sensor nodes in the network, $ToEnC(i)$ is the total energy consumption for each sensor node *i* and $ToPck_{snk}$ is the total packets received by the sink node.

2) **Energy Consumption:** This metric gives the energy consumption of nodes in the event area for transmitting a data packet to sink that given by

$$\boldsymbol{Energy\ Consumption} = \sum_{i=1}^{n} \boldsymbol{ToEnC(i)} \tag{19}$$

3) **Residual Battery Power:** This metric specifies the remaining charge of the battery attached to the node at the end of simulation.

4) **Packet Delivery Ratio (PDR):** This term can be declared as the ratio of successful received packets by the sink over the total number of packets transmitted by sources. Which is given by

$$\boldsymbol{PDR} = \frac{\boldsymbol{ToPck_{snk}}}{\sum_{i=1}^{x} \boldsymbol{ToPck(i)}} \tag{20}$$

where the $ToPck_{snk}$ is the total packets received by the sink node, *x* is the number of sources nodes and $ToPck(i)$ is the total number of packet sent by each sensor node *i*.

5.2 Discussion of the Experimental Results

The results obtained from the experiments conducted in this paper are discussed in more details in this section to validate the efficiency of the RRSEB in comparison with SensorAnt. The results were obtained from the QualNet simulator that offers high-fidelity simulations for wireless communication. The results are categorized into two parts based on the impact of the packet sent and different periods of time to show the accuracy of the proposed protocol.

5.2.1 The Impact of the Number of Packets Sent

In these experiments, we studied the effect of the number of packets sent on the performance of RRSEB in comparison with the SensorAnt scheme. The experiments were conducted in a WSN with 60 and 80 sensors deployment over 600×600 m^2 with 600s simulation time. As displayed in **Fig. 6**, we can see that increasing the number of packet sent results in the increase in the number of packets received by the sink in both schemes. These results show that the performance of RRSEB is better than that of SensorAnt since the RRSEB uses the new mechanism in the recovery phase. This mechanism allows the sender to track the backup routes if the failure occurs in the current path, thus resulting in a higher received packets advantage.

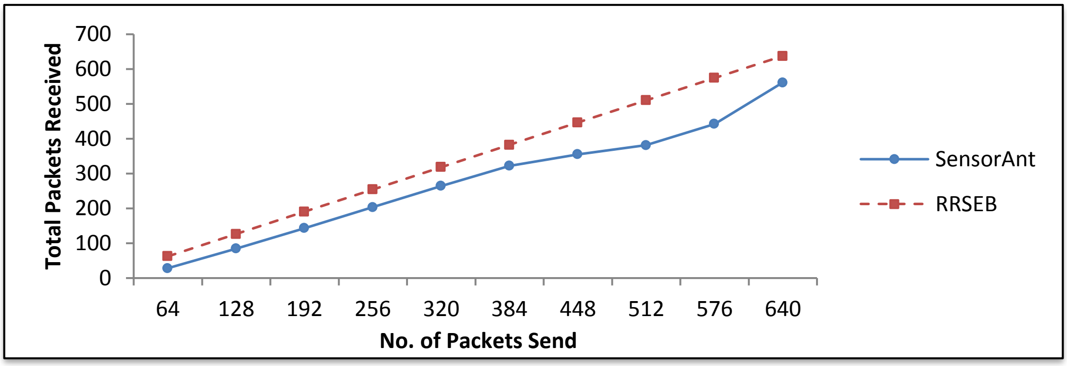

Fig. 6. Comparison of the total Packets Received by the sink between RRSEB and SensorAnt

Fig. 7 shows the packet delivery ratio under both schemes. These results reveal that the RRSEB outperforms SensorAnt by up to 54%, which means the number of packets dropped in the RRSEB is minimized to almost zero (i.e. no packet dropped). This implies that the RRSEB has a higher reliability than that of the SensorAnt. The increasing number of dropped packets in the SensorAnt is due to the use of the on-demand mechanism in case of occurrence of link failure which leads to an increase in the load inside the WSN and hence reducing the performance. Whereas, RRSEB uses both on-demand and proactive mechanisms, so in case of link failure, the proactive model builds multi-paths available that obviates the need to perform the path recovery setup, thus resulting in a decrease of packet loss. This makes the RRSEB scheme more reliable.

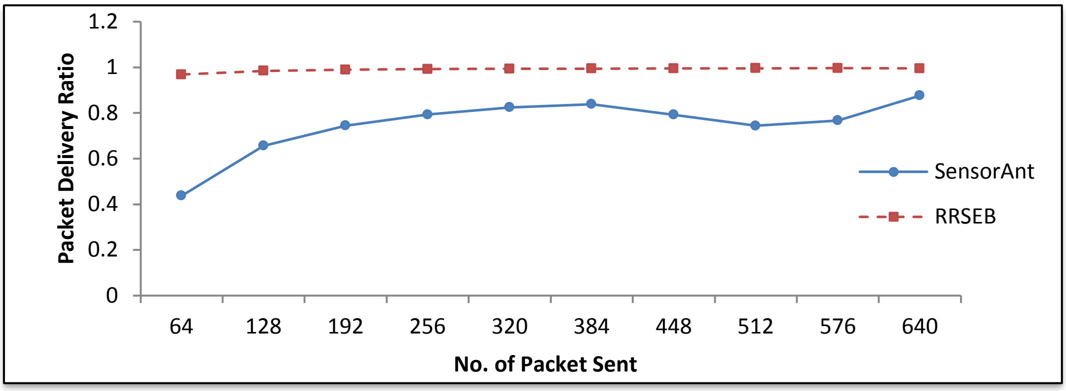

Fig. 7. The Results of Packet Delivery Ratio for RRSEB and SensorAnt

As shown in **Fig. 8**, it is clear that the RRSEB performs much better than the SensorAnt in terms of energy efficiency due to the higher number of received packets in the RRSEB. The plot showed that in both schemes, the efficiency decreases when the number of packets sent increases.

In **Fig. 9**, both algorithms balance the energy of the sensor nodes inside the WSN, and this is because both of them use the same method of searching the route with similar function assessment of the hop and path. The residual power capacity in the SensorAnt is slightly higher than that in the RRSEB, because more energy in the RRSEB is consumed during the computation process and control packets exchange in the recovery phase. Moreover, in RRSEB, the sensor's energy is not fully balanced, within a tolerable limit due to the use of proactive mechanism that searches for alternative routes causing some nodes to consume more energy than others. However, all the sensors in both schemes are still workable, meaning that they do not reach the level of deterioration or decay and their network lifetime can extend for a long period of time.

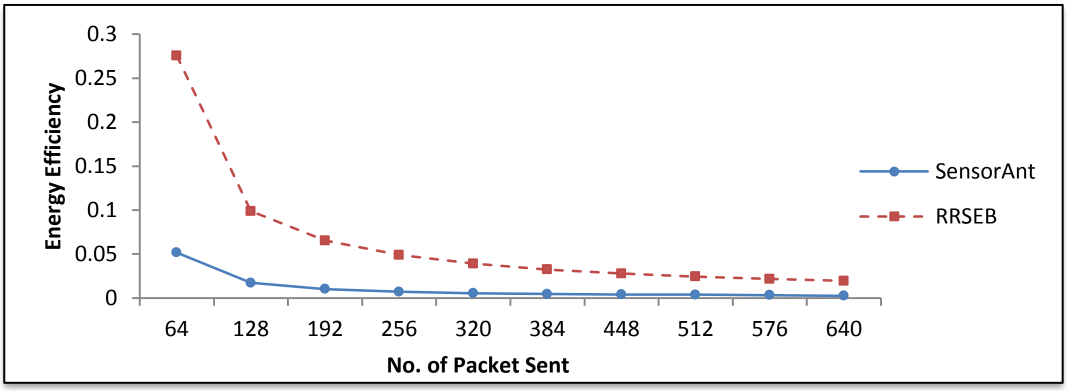

Fig. 8. The Energy Efficiency vs. No. of Packets Sent

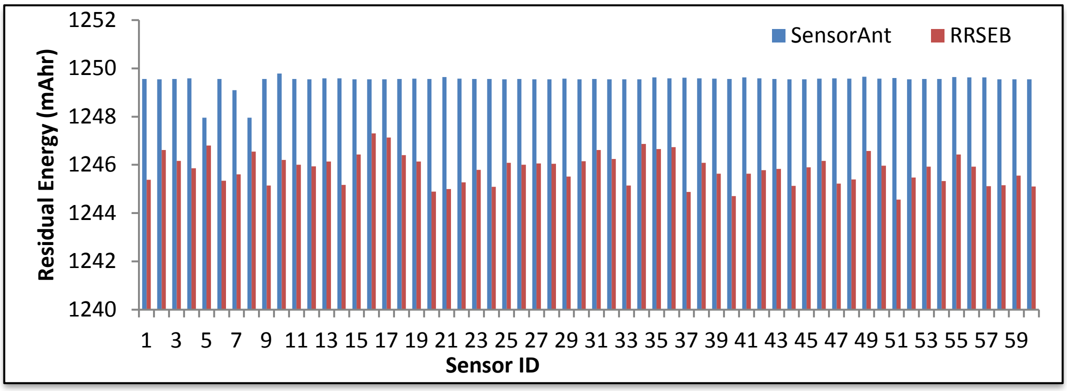

Fig. 9. The Energy Balancing of RRSEB and SensorAnt with 640 Packets Sent

The results in the following experiments were tested under the same conditions except the number of sensors this time is set at 80 sensor nodes. The results obtained are shown in Fig. 10, 11, 12 and 13 respectively. These results are consistent with the result obtained from previous set of experiments as shown in Fig. 6, 7, 8 and 9, respectively.

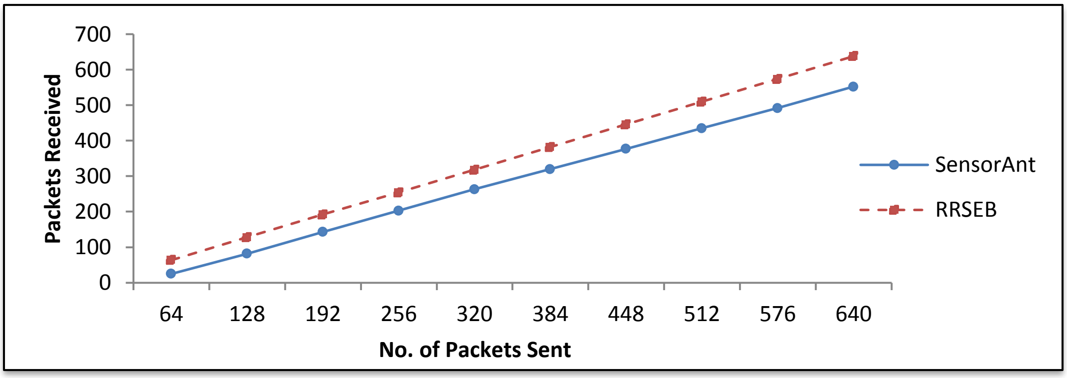

Fig. 10. Comparison of Total Packets Received by sink between RRSEB & SensorAnt at 80 nodes

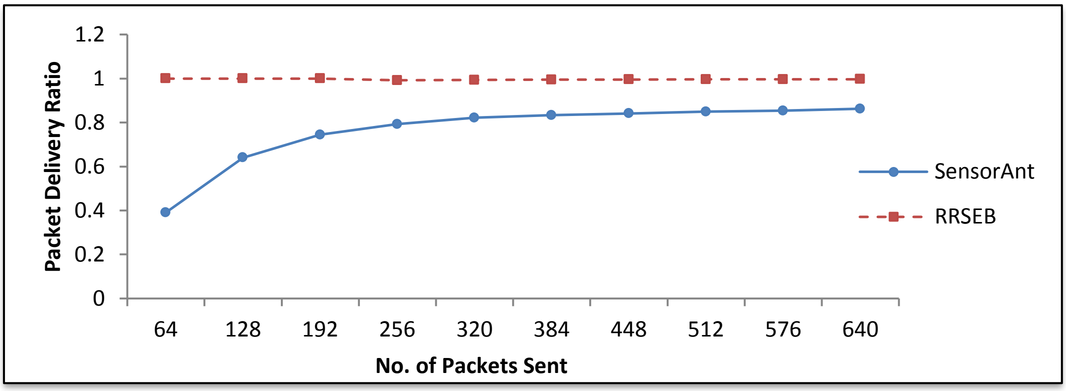

Fig. 11. The Results of Packet Delivery Ratio for RRSEB and SensorAnt at 80 nodes

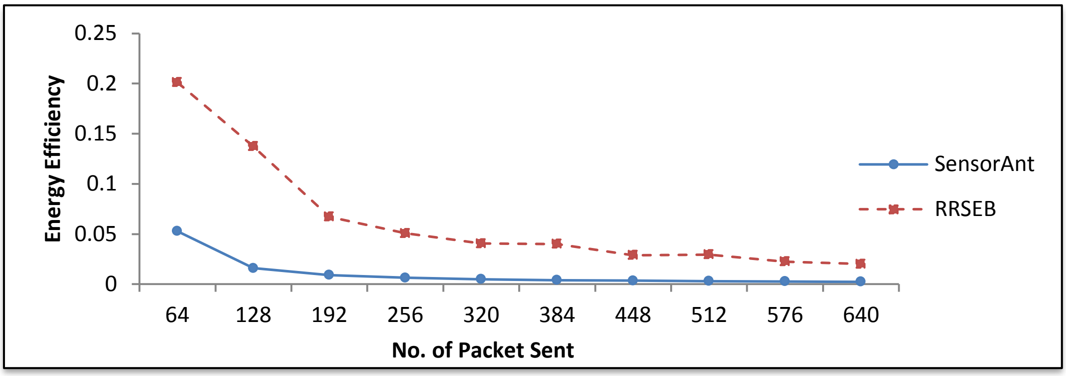

Fig. 12. The Energy Efficiency vs. No. of Packets Sent at 80 sensor nodes

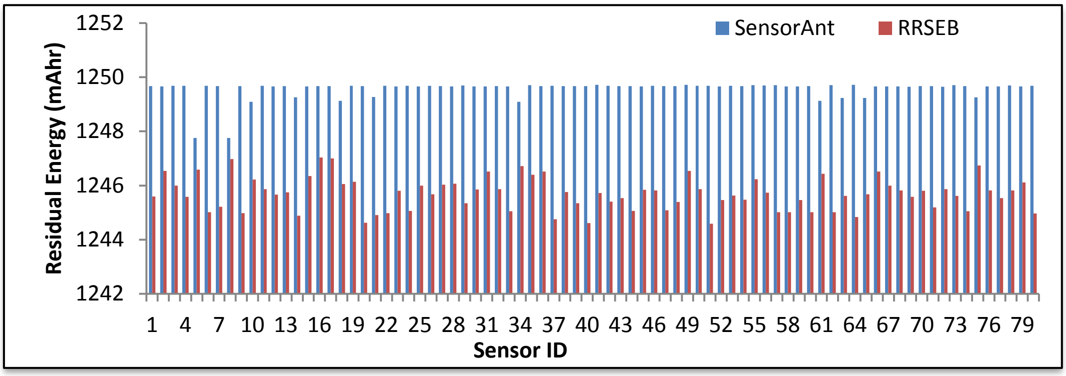

Fig. 13. Energy Balancing RRSEB and SensorAnt with 640 Packets Sent at 80 SNs

5.2.2 The Impact of Different Time Periods

In this section, experiments were conducted to study the effect of the various periods of time on the performance of RRSEB as compared to the SensorAnt scheme. The WSN include deployment of 80 sensors over 600×600 m^2 which were tested between 100 and 1000 simulation times.

The performance of the RRSEB is better than that of the SensorAnt by about 10% in terms of packet delivery ratio as displayed in **Fig. 14**. It can be seen that the packet delivery ratio, in both proposed schemes, decreases when the time increases since the congestion becomes more pronounced. However, the RRSEB in all cases still obtain a higher delivery and lower packet loss compared with SensorAnt, which implies that this method is considered as a reliable method even though in both methods their respective behaviors look similar; this is because they use the same technique during the path discovery process.

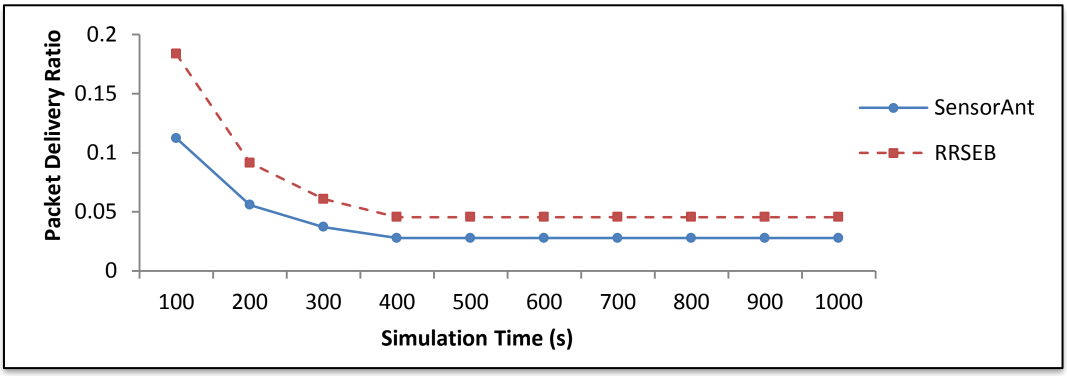

Fig. 14. Packet Delivery Ratio vs. Simulation Time

In terms of energy consumption, SensorAnt provides better results than RRSEB. This is evident since SensorAnt decreases the energy consumed by up to 4.5% less than the RRSEB as shown in **Fig. 15**. This is because the recovery process in RRSEB needs more control packets to exchange and more computation during the dissemination of pheromone and ant gathering processes to create multiple routes which consumes more energy. In addition, it is evident that in both mechanisms, as time increases the consumed energy increases too. To shows the difference of energy consumption clearly between both methods **Fig. 16** elaborated the percentage vs. time using the SensorAnt as a baseline.

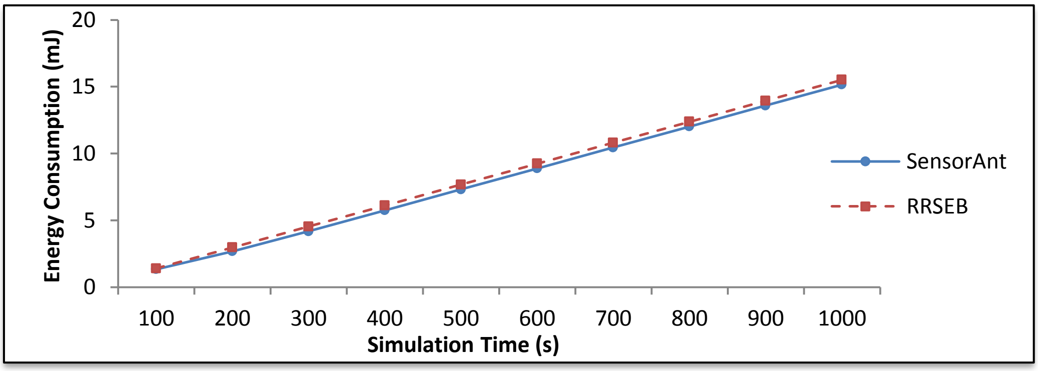

Fig. 15. Energy Consumption vs. Simulation of Time

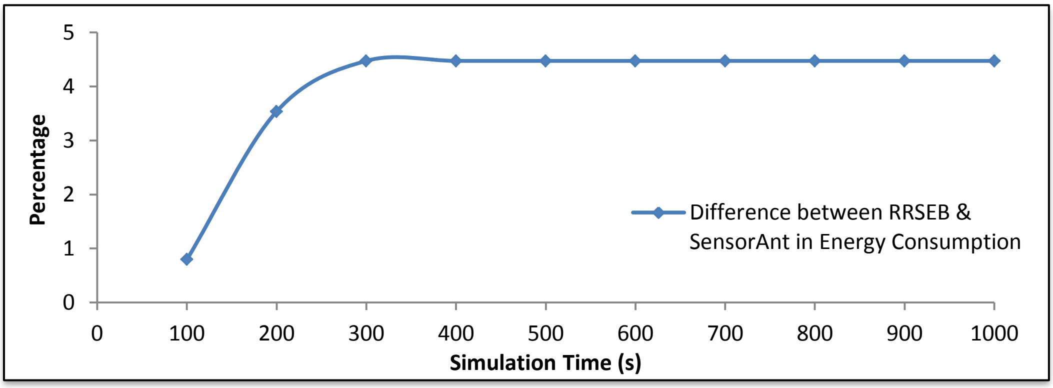

Fig. 16. Percentage vs. Time

In terms of energy balancing, both RRSEB and SensorAnt algorithms balance the energy of the sensor nodes inside the WSN. This is because both use the same method of searching the route with the same function assessment of the hop and path. Therefore, up to the end of simulation, all the sensors are still alive and the capacity of their batteries is depleted evenly in the network. So WSN still works with the full function and its life span is extended as shown in **Fig. 17**.

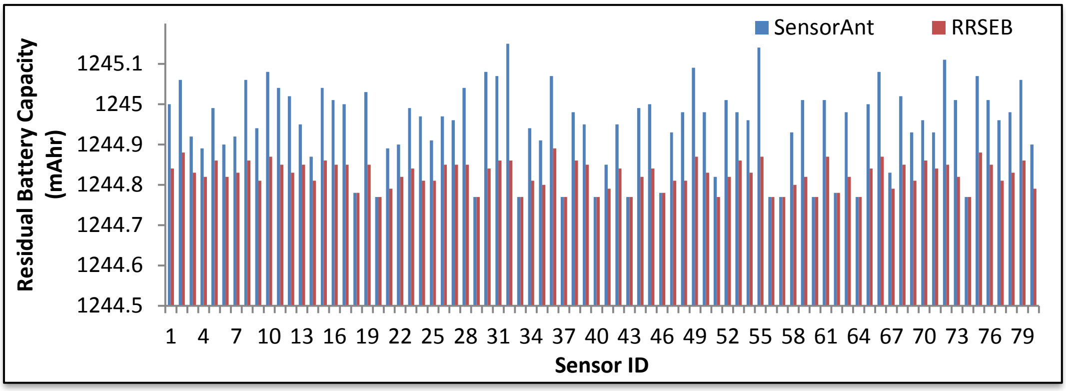

Fig. 17. The Results of Energy Balancing between RRSEB and SensorAnt at 1000 second

Fig. 18 shows the result of the proposed scheme RRSEB compared with the SensorAnt model in terms of lifetime for each sensor node. Again, both algorithms maintains a near equal lifetime for all the deployed nodes since it ensures that all nodes are used evenly. The sensor nodes in RRSEB model show a bit shorter lifetimes of the different sensor nodes while most of the nodes on SensorAnt still have the higher remaining energy. This is because the RRSEB consumed more energy than SensorAnt due to the needs of more control packets during the recovery phase.

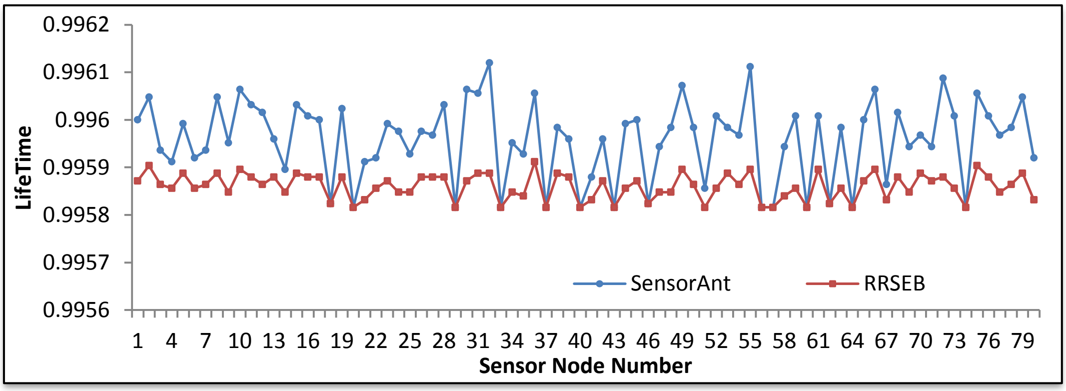

Fig. 18. The Lifetime for each sensor node at the end of simulation

6. Conclusion

In wireless sensor network applications, the guarantee of connectivity and monitoring the observed area is highly demanded. This paper presented a self-adaptive mechanism called RRSEB to ensure the reliability and efficiency of routing during the data transmission. The RRSEB concentrated on the recovery phase by adopting a method to deal with any dynamic changes in WSN. It used the dissemination of pheromone, which utilizes the current routing information to explore the potential paths by adapting the self-sustaining process. Next, the ant gathering operation used to examine and updates the new routes using the self-learning process. Finally, the RRSEB used to detection and correction the failures occurring in sensor networks. From the simulation results, the proposed RRSEB showed a better performance than the SensorAnt where decreasing the number of the dropped packets led to increasing the packet delivery ratio, thus enabling the system to show higher reliability.

References

[1] R. Zurawski, *Embedded Systems Handbook: Networked Embedded Systems*, 2nd ed. Boca Raton, Florida: CRC Press, 2009.

[2] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Computer Networks*, vol. 38, pp. 393-422, 2002. Article (CrossRef Link)

[3] F. Xia, "QoS Challenges and Opportunities in Wireless Sensor/Actuator Networks," *Sensors*, vol. 8, pp. 1099-1110, 2008. Article (CrossRef Link)

[4] N. A. Pantazis and D. D. Vergados, "A survey on power control issues in wireless sensor networks," *Communications Surveys & Tutorials, IEEE*, vol. 9, pp. 86-107, 2007. Article (CrossRef Link)

[5] S. C. Ergen and P. Varaiya, "On multi-hop routing for energy efficiency," *Communications Letters, IEEE*, vol. 9, pp. 880-881, 2005. Article (CrossRef Link)

[6] X. Wang, J.-J. Ma, S. Wang, and D.-W. Bi, "Cluster-based Dynamic Energy Management for Collaborative Target Tracking in Wireless Sensor Networks," *Sensors*, vol. 7, pp. 1193-1215, 2007. Article (CrossRef Link)

[7] A. El-Hoiydi and J. Decotignie, "WiseMAC: An ultra low power MAC protocol for multi-hop wireless sensor networks," *Algorithmic Aspects of Wireless Sensor Networks*, pp. 18-31, 2004. http://link.springer.com/chapter/10.1007%2F978-3-540-27820-7_4

[8] M. Chen, T. Kwon, S. Mao, and Y. Yuan, "Reliable and energy-efficient routing protocol in dense wireless sensor networks," *Int. J. of Sensor Networks - IJSNET*, vol. 4, pp. 104-117, 2008. http://www.inderscience.com/info/offer.php?id=19256

[9] C. Jae-Hwan and L. Tassiulas, "Maximum lifetime routing in wireless sensor networks," *IEEE ACM T. Network.*, vol. 12, pp. 609-619, 2004. Article (CrossRef Link)

[10] E. Bonabeau, M. Dorigo, and G. Theraulaz, "*Swarm intelligence: from natural to artificial systems*," Oxford University Press, USA, 1999.

[11] M. Dorigo, G. D. Caro, and L. M. Gambardella, "Ant algorithms for discrete optimization," *Artificial life*, vol. 5, pp. 137-172, 1999. Article (CrossRef Link)

[12] T. Camilo, C. Carreto, J. Silva, and F. Boavida, "An Energy-Efficient Ant-Based Routing Algorithm for ireless Sensor Networks," *Ant Colony Optimization and Swarm Intelligence*. vol. 4150: Springer Berlin / Heidelberg, 2006, pp. 49-59. http://link.springer.com/chapter/10.1007%2F11839088_5

[13] G. Singh, S. Das, S. V. Gosavi, and S. Pujar, "Ant colony algorithms for Steiner trees: an application to routing in sensor networks," *Intelligent Information Technologies: Concepts, Methodologies, Tools, and Applications*, V. Sugumaran, Ed. Oakland University, USA, 2008, pp. 1551-1575

[14] R. GhasemAghaei, A. M. Rahman, M. A. Rahman, and W. Gueaieb, "Ant colony-based many-to-one sensory data routing in Wireless Sensor Networks," in *Proc. of Computer Systems and Applications, 2008. AICCSA 2008. IEEE/ACS International Conference on*, 2008, pp. 1005-1010. http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=4493668&abstractAccess=no&userType=inst

[15] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *Proc. of 33rd Annual Hawaii International Conference on System Sciences (HICSS-33)*, Maui, Hawaii,USA, 2000, pp. 1-10. Article (CrossRef Link)

[16] K. Matrouk and B. Landfeldt, "RETT-gen: A globally efficient routing protocol for wireless sensor networks by equalising sensor energy and avoiding energy holes," *Ad. Hoc. Netw.*, vol. 7, pp. 514-536, 2009. Article (CrossRef Link)

[17] S. Lindsey and C. S. Raghavendra, "PEGASIS: Power-efficient gathering in sensor information systems," in *Proc. of IEEE Aerospace Conference*, Big Sky, MT, USA, 2002, pp. 1125-1130. Article (CrossRef Link)

[18] C.-S. Ok, S. Lee, P. Mitra, and S. Kumara, "Distributed energy balanced routing for wireless sensor networks," *Comput. Ind. Eng.*, vol. 57, pp. 125-135, 2009. Article (CrossRef Link)

[19] K. Sohraby, D. Minoli, and T. F. Znati, *Wireless sensor networks: technology, protocols, and applications*: Wiley-Blackwell, 2007.

[20] A. M. Shamsan Saleh, B. Mohd Ali, M. F. A. Rasid, and A. Ismail, "A Self-Optimizing Scheme for Energy Balanced Routing in Wireless Sensor Networks Using SensorAnt," *Sensors,* vol. 12, pp. 11307-11333, 2012. Article (CrossRef Link)

Ahmed Mohammed Shamsan Saleh Al-Mshreqi received the B.Sc degree in Computer Science from University of Baghdad, Iraq, in 2001. He received the M.Sc degree in Computer Science from department of Communication Technology and Network, Universiti Putra Malaysia, in 2008. He received the PhD degree in Communications and Networks Engineering at department of Computer and Communication Systems Engineering, Universiti Putra Malaysia, in 2012 . His main research interests are Wireless Sensor&Adhoc Networks, Energy management & control for wireless networks, Routing technologies, Bio-inspired mechanisms and Emerging wireless technologies standard.

Borhanuddin bin Mohd Ali obtained his BSc (Hons) Electrical and Electronics Engineering from Loughborough University in 1979; MSc and PhD from University of Wales, UK, in 1981 and 1985, respectively. He became a lecturer at the Faculty of Engineering UPM in 1985, made a Professor in 2002, and Director of Institute of Multimedia and Software, 2001-2006. He is currently the Director of Institute of Advanced Technology (ITMA). His research interest is in Wireless Communications and Networks where he publishes over 80 journal and 200 conference papers. He is a Senior Member of IEEE and a member of IET.

Hafizal Mohamad received the B.Eng. with First Class Honours and Ph.D. in Electronic Engineering from University of Southampton, UK in 1998 and 2003, respectively. He has been a faculty member at the Multimedia University, Malaysia from 1998. He served a short stint as a visiting fellow at National Institute of Information and Communication Technology (NICT), Yokosuka, Japan in 2005. Since 2007, he is a Senior Staff Researcher at Wireless Communications Cluster, MIMOS Berhad, where he leads a team of researchers working on cognitive radio and mesh network. He has published over 40 journal and conference papers. He has 3 patents granted and 15 patents filed. He is a Senior Member of IEEE and currently the Vice Chair for IEEE Malaysia Section. He was an Executive Committee of IEEE Malaysia Section, Educational Activities (2011-2012). He was a Chairman of IEEE Communication Society and Vehicular Technology Joint Chapter, Malaysia Section (2009 – 2011). He has been involved in organizing a number of conferences including; Technical Program Chair for APCC 2012 (Jeju, Korea), APCC 2011 (Sabah), MICC 2009 (Kuala Lumpur), and Tutorial Chair for ICT 2007 (Penang).

Mohd Fadlee A. Rasid is the deputy director for National Centre of Excellence on Sensor Technology (NEST) at Universiti Putra Malaysia. He received a B.Sc. in electrical engineering from Purdue University, USA and a Ph.D. in electronic and electrical engineering (mobile communications) from Loughborough University, U.K. He directs research activities within Wireless Sensor Network (WSN) group and his work on wireless medical sensors is gaining importance in health care applications involving mobile telemedicine and has had worldwide publicity, including BBC news. His research interests are Mobile Telemedicine, Wireless Medical Sensors, Wireless Sensor Networks, Personal Area Network: Bluetooth and ZigBee Technology.

Alyani Ismail received her BEng (Hons) Electronic and Information Engineering from University of Huddersfield, United Kingdom in 1999. She received her MSc in Communication, Computer and Human-Centred Systems Engineering in 2001 and her PhD in Electronics Engineering majoring in micromachined microwave devices in 2006 from University of Wales, UK. Her research in micromachined filter design at Birmingham was sponsored by the UK Engineering and Physical Science Research Council. She became a lecturer at the Faculty of Engineering, Universiti Putra Malaysia (UPM) in 2006. Her research interest specializes in the development of microwave devices particularly passive filters and antennas.