Bio-Inspired Technique:An Adaptive Routing for Reliability and Energy Efficiency Method in Wireless Sensor Networks

Ahmed M. Shamsan Saleh

Faculty of Computers & Information Technology (FCIT), University of Tabuk, 71491, Tabuk, Saudi Arabia

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. Some WSN applications require the energy-efficient and link reliability as important performance parameters. Hence, this paper presents a routing protocol that considers these two criteria. We propose a new mechanism called Reliable and Energy Efficient Routing (REER) to reduce the packets drop during data communications. It is an adaptive method to ensure high routing reliability in if failures occur due to the movement of the sensor nodes or when sensor node's energy depletion. This is accomplished by introducing a new method to create alternative paths together with the routing information obtained during the route detection stage. The goal of this operation is to update and offer new routing information in order to determine multiple possible paths to increase reliability of the sensor network. Simulation results demonstrate that the proposed method shows better results in terms of packet delivery ratio and energy efficiency.

Keywords: *Reliability, Energy Efficient, Link Failure, Swarm Intelligence, Ant Colony.*

1. Introduction

Wireless sensor network (WSN) is a group of sensor nodes 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. Since sensor node has a limited battery power which may not be replaceable once deployed, it is therefore vital for the WSN to be equipped with energy-efficient mechanism [2]. One of the ways to an extended network lifetime is by ensuring that the sensor network is energy balanced. Figure 1 shows a typical wireless sensor network architecture consist of sensor nodes and sink node that is connect via the internet to transmitted the collected data for further processing , analysis or storage.

There are many challenges associated with WSNs and other distributed networks despite their similarities. These constraints affect the design of WSN, whereby it leads to the need to develop protocols considering various constraints in WSN environments. Some of the most significant constraints of sensor networks are listed below:

Energy: The restriction is most often associated with the design of sensor nodes with limited battery power. Typically, they are equipped with batteries that have to be replaced or replenished, if they are exhausted. In most cases, it is very difficult to do this especially in harsh or remote areas. Therefore it is very important to manage the energy consumption in order to conserve energy and survive longer.

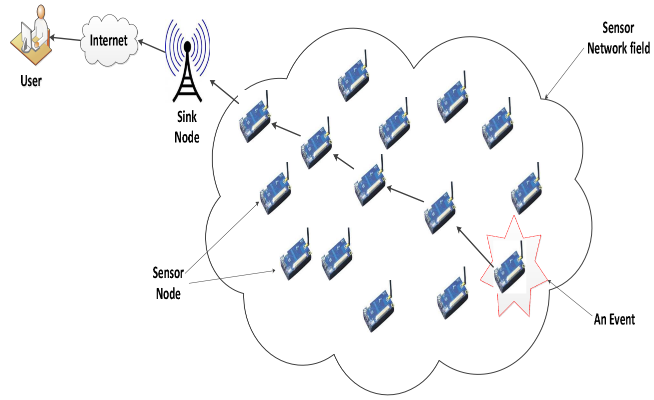

Figure 1. Typical wireless sensor network architecture

Self Organization: Most of WSN applications work in inaccessible or remote environments, without the assistance of the infrastructure or the ability for maintenance needs. For this reason, sensors must be able to self organize by configuring itself and collaborating with each other. The sensors should cooperate and adapt to failures and changes in the phenomena without any external intervention.

Distributed Control: The constraints of the large network sizes and limited power of many wireless sensor networks makes it impractical to use centralized protocols to execute network control solutions like topology and routing control. Alternatively, the sensors need to cooperate with their respective neighbors to make a local decision without any global information. Hence, the outcome of these distributed protocols lead to more energy efficiency than centralized ones.

Scalability: Most of the node's deployment in WSN is based on its specific applications. While the distribution of high density nodes in sensor networks provide redundancy and enhance fault tolerance of the networks, it also introduces scalability problems. The deployment of sensors, for sensing and monitoring the event's occurrence, could involve hundreds or thousands nodes. Therefore, WSN protocols should be able to deal with large numbers of sensors in an efficient way.

Swarm Intelligence (SI) algorithms have been proposed to overcome the challenges in WSN. Ant Colony Optimization (ACO) is possibly the best studied field in SI to optimize routing issues in communication networks. SI is the basis of studying the collective behavior of distributed, self-configuring principles such as ant colonies [3]. 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 i.e. pheromone trace and this process is called stigmergy. The detail of ACO algorithm can be found in [4].

Data routing is a very critical process in WSNs due to the constraints of the communications range [5]. Therefore, it is preferable to forward packets from the collection area to the sink or base station by multiple hops and paths in order to reduce the sensors energy consumption and packets dropped for long distance transmission [6] . Therefore, in this paper we proposed a routing protocol that taken into consideration energy awareness by utilizes the battery power efficiently in order to prolong the lifetime of network. Moreover, it distributes the traffic load across multi-paths to reduce the packets drop and increases the reliability of the networks. By combining the simplicity of SI with the efficiency of diffusion scheme in routing, we design this protocol for energy-efficient and reliable routing based on ACO.

The rest of this paper organized as follows. Section II reviews some of the related work. Section III describes in detail our proposed protocol, while Section IV presents the performance evaluation of our new method. Finally, Section V concludes our work.

2. Related Works

Sensor node has to work with low transmission power aiming to extend lifespan of the sensors while ensuring the sensors are within communication rang. In most WSN applications, the guarantee of connectivity and monitoring the observed area is highly important. Hence, the protocol design should take into consideration the energy aware mechanism and increase the reliability by using alternative routes as backup and restore it when the failures occurrence during the packets' transmission.

In [7], the authors first proposed a routing based-on centralizing offline ant colony system to solve the Steiner tree problem. Later they presented a distributed online-based method 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 sensor nodes. The object is then to obtain a Steiner tree of minimum cost when forwarding packets to the sink. The authors built their method using a unique base-station. This scheme introduces a good design for multicasting trees in WSNs. Moreover, the authors suggest that the destination creates the ants-backward only after the entire ants-forwarded are received, and the same condition can be applied to the ants-forwarded which will not be created from the sensors until all the ants-backward are back. This method is difficult to achieve in reality as some ants may be lost during the transmission process, which is normal in unreliable sensor networks.

Many-to-One Improved Ant Routing was proposed for upstream routing many-to-one sensing packets [8]. The routing algorithm is linked with a congestion control scheme that helps to alleviate the collisions. The protocol is divided into two stages. During the first stage, it finds the shortest route between any sensor 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 sensor, the target, and their neighbors are known. The disadvantage of this method is that the selection of the best route is based only on the distance, and there is no consideration of the residual battery power.

Ant-aggregation method of sensor networks was proposed in [9]. Their method used multi-hop connections, including in-network processing resulting in significant improvement in the lifespan of the WSN by decreasing battery power demands. Their method constructs the trees that satisfy the smallest cost accumulation. Furthermore, the mission of the ants is to find the shortest route to sink or to the closest aggregation node.

A novel Energy-Efficient Cooperative Communication (EECC) scheme for the WSN grants the reliability and efficiently during packet's transmission against unreliable connections [10]. However, in their method cooperative-relay is executed at each intermediate hop from sender to destination. If any sensor fails to accept the packets from upstream source-node, the closest sensors that already overhearing the packets will begin the cooperation in a proactive manner. Where it will choose the best cooperative-relay among them to contribute in the communication session. Their proposed method used in cross layer between the routing and MAC layers.

In [11] the authors proposed an efficient power aware routing technique for wireless heterogeneous sensor networks , this technique offer loop free, stateless, source to destination routing without any prior- knowledge from neighbors . The proposed method employed both symmetric and asymmetric links when data routed from sender-to-receiver. The sender sensor transmits its location information to all neighboring sensors. After that, each sensor receive this information starts computes delay according to the data acquired from sender in order to forward its power-value. Sensor that has a least delay resends its power earlier than the other sensors during contention-phase. Based on that delay-slot the scheme will select inappropriate low power sensors at that time. The proposed scheme creates an efficient data-route which guarantee that data received by to the sink. Using this efficient power-aware routing technique resulted to stateless, energy-efficient sender to sink routing at low-communication overhead without using previous neighbor knowledge. The performance of the proposed scheme shows that it outperforms all compared methods in terms of consumed power and delay. The main drawback in scheme that all the neighboring sensors which participate in contention-process wasting their power level due to delay based individual reply. Another issue that the proposed method is loop free assuming no failures in greedy forwarding.

3. The Proposed REER Technique

WSNs have strict energy requirements and may experience dynamic changes in the environment. We propose a new technique called Reliable and Energy Efficient Routing (REER) to take into consideration these constraints with 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 occur in the routes.

3.1 REER Energy 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. In this paper, we use simple energy model according to [12] .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:

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

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

$$EnC^{Tx}(x) = EnC^{elec} * N + EnC^{amp} * N * d^2 \quad (2)$$

where EnC^{elec} is the electronic circuit energy consumed due to the transmitter, which is equal to 50nJ/bit , EnC^{amp} is the energy consumed by the power amplifier, which is equal to 100pJ/bit/m^2 ,and d represent the distance.

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

$$EnC^{Rx}(x) = EnC^{elec} * N \quad (3)$$

where EnC^{elec} is the electronic circuit energy consumption at receiver, which is equal to 50nJ/bit.

3.2 REER Packets

In REER technique, the packets are classified based on the operation that used during the routing processes either a request Ant-Forward (F-ANT) or a reply Ant-Backward (B-ANT). During the route detection 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 route 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.

3.3 Routing Tables

Each sensor node x maintains a pheromone table or routing table R_x. Each entry in the table R^z_{xy} includes the information of the path from sensor x to the sink node 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 sink node z through its neighbor y, gathered by Ant-Forward (F-ANT) and updated by Ant-Backward (B-ANT). The non-real pheromone indicates the alternative path quality from sensor x to the sink z through its neighbor and is obtained during route recovery stage by using the reinforcement learning mechanism. The 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.

3.4 REER Description

REER employs both on-demand and proactive mechanisms, whereby the on-demand process will be triggered when the sensor node has a data packet to be sent to the sink and 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.

The first function of REER is the detection phase which finds the routes from the source node the sink node using the reactive mechanism. The second function is the recovery phase which comprises of two operations namely the spreading of pheromone and the ant assembling operation using partially proactive mechanism. These operations aim to discover alternative routes, and to fix the existing path by sending control packets. After creating the path in detection phase, during the session of communicating and sending the data packets between the sensors, the REER begins to search for new available paths and updates the information of the current routes to increase its reliability and detect failures. We introduce two new concepts in this recovery phase using a proactive scheme called self-sustaining and self-learning. Self-sustaining disseminates information about the current pheromone value on the sensor node, using packets at regular intervals. This operation facilities to identify potential routes. On the other hand, self-learning monitors and updates the routing information during communication session. It validates the routes resulting from prior operations. Additionally, the REER employs periodic packets used in self-sustaining to check the presence of neighboring sensors in order to adjust their routing tables when links' failure occurs.

3.4.1 Route Detection process

When the sensor senses data to forward to the base-station, 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 to find out the route to the sink. Otherwise it will send unicast F-ANT 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^z_{xy} given as follows:

$$Pr^z_{xy} = \frac{(P^y_x)^\beta}{\sum_{y \in N^z_x} (P^y_x)^\beta} \quad (4)$$

where P^y_x 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 message from the sensor node x to the sink z through y, it starts assessing the function quality of the ant route, $F(ph)^z_{xyz}$ as follows:

$$F(ph)^z_{xyz} = F(ph)^y_{xyz} + EnC^{Tx}_{xy} / F(hop)_{xy} \quad (5)$$

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

$$F(hop)_{xy} = e^y * e^y_{av} * (1/(e^y_{nw} * l^y)) \quad (6)$$

where e^y is the current residual energy of sensor y. e^y_{av} is the average residual energy of the route from sender x until the current sensor y. l^y is route length up to y and e^y_{nw} 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 and B-ANT using:

$$e^y_{nw} = \alpha e^x_{nw} + (1 - \alpha) e^y_{nw} \quad (7)$$

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

Consequently, based on the hop function $F(hop)_{xy}$, our model satisfies the balancing of energy consumption that reduces sensor 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. 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. (8) 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 means a better path will be chosen. As a result, the protocol will use this to update the pheromone trail P_x^y at the pheromone table as follows:

$$P_x^y = (1-\omega)P_x^y + \Delta P_{xyz}^z \quad (8)$$

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:

$$\Delta P_{xyz}^z = 1/F(ph)_{xyz}^z \quad (9)$$

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

When the sink node receives the F-ANT it will generate B-ANT to begin the route reply by using the unicast operation using the same path used by the F-ANT forwarded to the sender node. During the route reply stage using B-ANT, each sensor that receives the ant updates its routing table using Eq.(8). When B-ANT reaches the final target sensor *-the sensor generates F-ANT-* 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.

3.4.2 Route Recovery Process

The REER operations concentrate on the enhancement of the route recovery process by using the proactive route method to create alternative paths together with the pheromone knowledge obtained through the route detection stage. These operations will update and offer new routing information by constructing the multi-paths from the sender sensor to the sink in order to increase the reliability during the data transmission. The proactive scheme of the route recovery used in REER consists of two main processes namely, the spreading of pheromone and the ant assembling process, respectively. Spreading of pheromone is designed to distribute information about the current pheromone on the sensor nodes using control packets at regular intervals. On the other hand, the ant assembling operation uses the proactive method to monitor and update the pheromone data with F-ANT$_p$ based on the real or non-real information resulting from the previous operations. This operation is only associated to each unique session which begins and finishes with it. However, the spreading of pheromone is performed by all sensors during their life span.

(a) Spreading of Pheromone

The route detection process uses the reactive ants which lead to the availability of a unique route 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. This spreading 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.

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. Specifically, 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 $F(hop)_{xy}$ between two neighboring sensors *x* and *y*, which is described in the Eq. (6). As the result, the self-sustaining will be extended as:

$$F(S_{sus})_{xy}^z = 1/\left((1/P_x^z) + F(hop)_{xy}\right) \quad (10)$$

where the $F(S_{sus})_{xy}^z$ represents the self-sustaining pheromone value.

(b) Ant assembling Process

The ant assembling operation is one of the major components of REER scheme. 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 to the end of the session. This will 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 spreading pheromone operation as previously explained. While the first one guides the ants to renew the best-quality value of the available routes, the second one enables those ants to explore new routes derived from the suggestions offered throughout the spreading pheromone operation.

In the ant assembling 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.

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 assembling 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 as a self-learning behavior.

(c) Detection and Correction of Failures

This subsection explains how the REER handles the occurrence of failures during forwarding of the packets either in the form of data or control. If the failure occurs is due to failure of forwarding the control packet, then the sensor in REER starts to broadcast a packet notification error. 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.

The dissemination 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.

If the sensor notices a missing connection with any neighbor, it updates its routing table and creates a packet notification error. 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 notification error. Subsequently, 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. 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.

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 notification error to the sink node. Therefore, the data message is still to be 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 route detection processes.

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 detection 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 now starts transmitting the data packet to the sink.

4. Performance Evaluation

We investigate the performance of proposed scheme through computer simulation. The proposed REER scheme is simulated by deploying 80 sensor nodes over 600×600 m^2 with 600s simulation time. The other parameters used in the simulation are listed in the Table 1.

TABLE 1. SIMULATION PARAMETERS

Name	Value
Channel Frequency	2.4GHz
Traffic	CBR
Packet Size	32 byte
EnC^{elec}	50nJ/bit
EnC^{amp}	100pJ/bit/m^2
Data Rate	250Kbps
Initial Energy	1250 mJoule

Two performance metrics are used to evaluate and validate the effectiveness of the proposed scheme, namely packet delivery ratio and energy efficiency.

Packet Delivery Ratio is the ratio of successful received messages by the sink over the total number of messages transmitted by sources.

Energy Efficiency is the ratio between total consumed energy over the number of packets received by the sink-node.

To evaluate the performance of the proposed REER, we have conducted the performance comparison with SensorAnt method [13], simulated under the same conditions.

Figure 2 shows the packet delivery ratio for both schemes. These results reveal that the REER outperforms SensorAnt, which means the number of packets drop in the REER is minimized to almost zero. This implies that the REER 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 the case of link failure occurrence. On the other hand, REER uses both on-demand and proactive mechanisms. 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 REER scheme more reliable compared to SensorAnt method.

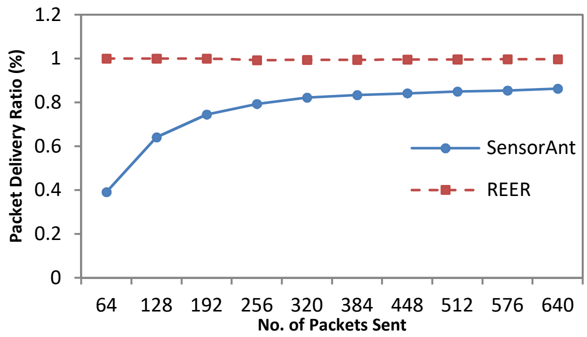

Figure 2. Packet Delivery Ratio Comparsion for REER and SensorAnt.

Next, we evaluate the energy efficiency for both schemes and the simulation result is shown in Figure 3. It is clear that the REER performs much better than the SensorAnt in terms of energy efficiency due to the higher number of received packets in the REER. The plot showed that in both schemes, the efficiency decreases when the number of packets sent increases. This is evident as the increase in the number of packets will consume more energy during the transmission time.

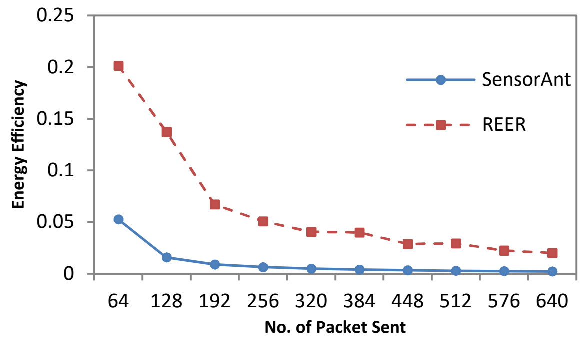

Figure 3. Energy Efficiency Comparsion for REER and SensorAnt

5. Conclusion

In wireless sensor network applications, the guarantee of connectivity and monitoring the observed area is highly critical. This paper presents an adaptive mechanism called REER to ensure the reliability and efficiency of routing during data transmission. The REER focuses on the recovery phase by adopting a method to deal with any dynamic changes in WSN. It employs the spreading of pheromone, which utilizes the current routing information to explore the potential paths by adapting the self-sustaining process. Next, the ant assembling process is involved to examine and updates the new routes using the self-learning process. Finally, the REER performs detection and correction the failures occurring in sensor networks. Simulation results, indicates that the proposed REER show better performance than the SensorAnt. It is observed that REER reduces the number of packet drop which leads to high packet delivery ratio. REER also exhibits better energy efficiency compared to SensorAnt method.

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