Chapter 5

Energy-Balanced Routing Algorithm in a Wireless Sensor Network

5.1 Introduction:

WSN is considered to be a self-organized wireless network system which comprises of numbers of energy-limited micro sensors beneath the umbrella of industrial application (IA) [108 - 109]. Nowadays, WSN is proven to be an effective medium to integrate, physical world and information world of IA [69- 72]. In general in the sensor networks, each sensor node i.e. both a sensor and a router, and its computing ability, storage capacity, communication ability and power supply are limited. Therefore, for the study of large-scale WSN communication system, design of network topology, routing algorithm and protocol plays a very fundamental and important role [73 - 78]. Recently, multiple mechanisms are applied to WSN topology control and routing designing in order to balance the energy consumption and to maintain coverage and connectivity [79 - 80].

The study involves the large-scale WSN for static data collection and event detection under the banner of Industrial application. It takes the balance routing of energy distribution into account. Based on the detailed analysis of the data transmission mechanism of WSN, this algorithm quantify the forward transmission area, define forward energy density. The forward energy density thus defined by the algorithm, constitutes forward-aware factor with link weight and propose a new energy-balance routing protocol based on forward-aware factor (FAF-EBRM). Thus balances the energy consumption and prolongs the function lifetime.

Since, all the nodes must compete in CH election, this routing protocol increases the control overhead complexity.

This algorithm i.e. Energy-Balanced Routing Method Based on Forward-Aware Factor proposed by Degan Zhang, Member, IEEE, et al. [26] in IEEE Transactions On Industrial Informatics, Vol.10, No.1, February 2014. In this chapter our first aim is to provide a detailed analysis of the data transmission mechanism of WSN, followed by computation of forward transmission area, defining forward energy density, which constitutes forward-aware factor with link weight and then propose a scheme of new energy-balance routing protocol based on forward-aware factor (FAF-EBRM) and at last we evaluate this algorithm with some performance matrices like Energy values, Latency values, Packet Delivery Ratio and Residual Energy Values and discuss the result.

5.2 Basic BBV Weighted Network Model and Local-World Theory:

Based on the reported research work, the topology evolving of BBV model can be divided into four stages as follows [86].

1) Initialization: The initial network contains N_0 nodes and a few edges ($w = w_0$). Here, w_0 is the initial weight, and the variable parameter of weight w *is* w_0.

2) Growth of topology: At each time step, a new node *n* with *m* edges ($w = w_0$) joins the existing network.

3) Preferential attachment: The existing nodes are preferentially attached by *m* edges in step 2 with probability $p_{n->i}$.

$$p_{n\to i} = s_i \Big/ \sum\nolimits_j s_j \qquad (5.1)$$

where $n \rightarrow i$ means node n to node i, the vertex strength s_i is defined as the sum of edge wights connected to it: $s_i = \sum_{j \in N(i)} w_{ij}$, w_{ij} is the weight between node i and node j, $N(i)$ is the set of neighbour nodes (directly connect to node i). The vertex strength s_j is smaller.

4) Update of strength and weights (as shown in Figure 5.2.1)

The addition of edge (n, i) not only changes the strength of i, but also changes the weights between i and its neighbours

$$w_{ij} \rightarrow w_{ij} + w_{ij} \quad (5.2)$$

Where,

$$\Delta w_{ij} = \delta \frac{w_{ij}}{s_i} \quad (5.3)$$

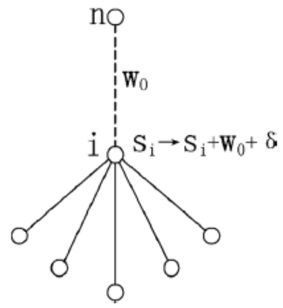

Figure 5.1: Change of node strength.

Here, δ is a positive or negative increment. After the update, repeat steps 2) to 4), until the evolving is completed. As an assumption, letting $w_0 = 1$, when $t \rightarrow \infty$, the distribution of edge weight is

$$P(w) \sim w^{-\alpha} \quad (5.4)$$

The distribution of the node degree is

$$P(k) \sim k^{-\gamma} \quad (5.5)$$

and the distribution of node strength is

$$P(s) \sim s^{-\gamma} \quad (5.6)$$

where

$$\alpha = 2 + 1/\delta,\ \gamma_k = \gamma_s = \gamma = (4\delta + 3)/(2\delta + 1) \quad (5.7)$$

Here δ also is a positive or negative increment. In a local-world evolving network model is proposed by Li and Chen [76]. The study shows that, in the real network, a node can only connect to special group of nodes rather than any node in the whole network. *M* nodes are randomly selected from existing nodes as the local world of the new node *n*, and preferential attachment probability is defined as

$$p_{Local}(n \to i) = p'(i \in Local - world)\frac{k_i}{\sum_j k_j} \quad (5.8)$$

where

$$p'(i \in Local - world) = M/(N_0 + t) \quad (5.9)$$

Here, M ($M \leq N_0$) nodes from the existing network as the local world of new sensor node together with *m* new edges, and *t* is time parameter. In the BBV model, *m* existing nodes from the entire network are selected to connect to the new node *n*, which is not feasible in a WSN of IA due to the limited communication range and energy of sensors. Thus, the local-world theory is needed, that is to say, *n* can only connect to the sensors within a specific range. Similarly, in SCN, scientists tend to cooperate with others who work in the same country or discipline; in WWAN, the length of a flight is always shorter than the maximum range of a plane, which can be seen as the examples of the local world [76 - 79].

5.3: Forward- Aware Factor-Based Energy-Balanced Routing Algorithm:

Based on the detailed analysis of the data transmission mechanism of WSN, we quantify the forward transmission area, define forward energy density, which constitutes forward-aware factor with link weight, and propose a new energy-balance routing protocol based on forward-aware factor, thus balancing the energy consumption and prolonging the function lifetime.

5.3.1 Network Model

As shown in Figure 5.2, suppose sensor nodes are randomly distributed in a $W \times H$ rectangular sensing field. Data are sent to the regional central node (cluster head), then transferred to the sink node (Sink). The descriptions and definitions are as follows.

1) All sensor nodes are isomorphic, and they have limited capabilities to compute, communicate and store data. The set of sensor nodes is defined as $V = (v_1, v_2, \ldots, v_N)$, and N is the total number of nodes, $i = 1, 2, \ldots, N$. Here, i is the identifier for a node
2) The energy of sensor nodes is limited, and the initial energy is E_0. Nodes die after exhausting energy entirely. However, the energy of the sink node can be added. Locations of nodes and Sink do not change after being fixed, and a node cannot obtain the absolute position depend on its own location device.
3) Nodes can vary transmission power according to the distance to its receiver. The sink node can broadcast message to all sensor nodes in the sensing field. The distance between the signal source and receiver can be computed based on the received signal strength. Regional central nodes are not selected at the beginning, on the contrary, they spring up during the topology evolution. Important nodes have more connections, whose degree and intensity are significantly higher than neighbor nodes.

The energy model is the free space model [74]. The energy spent for sending a *l*-bit packet over distance *d* is

$$E_{Tx}(l,d) = E_{Tx-elec}(l) + E_{Tx-amp}(l,d) = \begin{cases} lE_{elec} + l\varepsilon_{fs}d^2, & d < d_0 \\ lE_{elec} + l\varepsilon_{mp}d^4, & d \geq d_0 \end{cases} \quad (5.10)$$

where

$$d_0 = \sqrt{\frac{\epsilon_{fs}^2}{\epsilon_{mp}}} \tag{5.11}$$

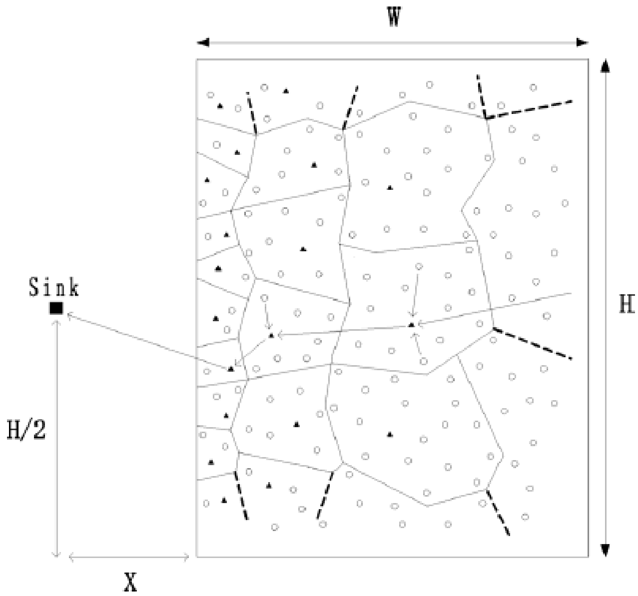

Figure 5.2: Distribution map of sink and sensor node [108].

and $\in_{fs}$, $\in_{mp}$ are the energy coefficients. The energy spent for receiving data is defined as

$$E_{Rx}(l) = E_{Rx-elec}(l) = lE_{elec} \tag{5.12}$$

where E_{elec} is a fixed energy value spent for sending 1-bit data. When the data transmission distance is larger than threshold d_0 , the energy consumption would rise sharply, so the maximum communication radius of common sensor nodes is set to d_0.

Definition 1: As shown in Figure 5.2, the distance between *i* and *Sink* is *d(i, Sink)* and is given by

$$d(i, Sink) \in \left(X, \sqrt{(H/2)^2 + (X+W)^2} \right) \tag{5.13}$$

Definition 2: As shown in Figure 5.2, the communication radius can be controlled, in order to construct a topology with uneven clusters, when i is the cluster head, the cluster radius is $R_{opt}(i)$:

$$R_{opt}(i) \sim f_1\left(d\left(i, Sink\right)\right) \tag{5.14}$$

Where $f_1(d(i, Sink))$ is a function for $d(i, Sink)$, and

$$f_1\left(d\left(i, Sink\right)\right) \in \left(0, d_0\right) \tag{5.15}$$

Definition 3: At time t, the weight between i and j is w_{ij} given by

$$w_{ij}(t) = \frac{\varsigma\left(E_i(t) E_j(t)\right)^{\psi}}{\left(d\left(i, j\right)^2\right)^{\eta} \left(T_{ij}(t)\right)^{\xi}} \tag{5.16}$$

where ζ, ψ, η, ξ are non-negative constants, $E_i(t)$ and $E_j(t)$ are residual energy, $d(i, j)$ is the distance between two nodes, and $T_{ij}(t)$ is the data flow of the edge (communication link) e_{ij}. Set the distance from i to *Sink* further than j, and then

$$T_{ij}(t) \propto f_2\left(d\left(i, Sink\right), t\right) = t \Big/ \left(d\left(i, Sink\right)^2\right) \tag{5.17}$$

where $f_2(d(i, Sink), t)$ is a decreasing function of $d(i, Sink)$ and an increasing function of time t. The amount of data is smaller when the edge-end node is further away from sink node.

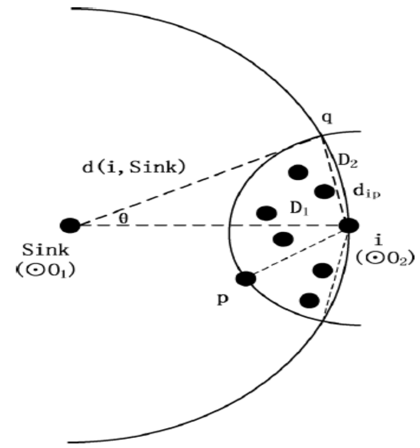

Figure 5.3: Forward transmission area.

As time goes on, the amount of data becomes larger with the increase of nodes. In this definition, edge weight w_{ij} represents the communication capacity. In equation-(5.16), when *d (i, j)* is long, the data transmission tends to choose a short-distance link. Similarly, when $T_{ij}(t)$ is large, the communication link is busy, the data transmission choose low-load link firstly. Energy plays a key role in edge weight, when the residual energy of *i* and *j* is sufficient, e_{ij} (the edge from *i* to *j*) is stronger for data transmission.

5.3.2 Establishment of the Model

Definition 4: The forward transmission area of node *i* is FTA(*i*). Figure 5.3 shows that $\odot_1$ is a circle with *Sink* as the center and *d(i, Sink)* as the radius, $\odot_2$ is a circle with *i* as the center, and d_{ip} as the radius:

$$FTA(i) = \odot 0_1 \cap \odot 0_2 \tag{5.18}$$

$$d_{ip} = \max\left(d_{ij}\right), j \in N'(i) \tag{5.19}$$

where *N(i)* is the set of nodes that have communication link with node *i, N'(i)* is the set of nodes of *N(i)* that have an edge with node *i*, and d_{ij} is the distance of node *i* and node *j*.

Figure 5.3 shows that, in WSN clustered hierarchical routing protocols, sometimes nodes of a cluster are closer to the sink than the cluster head is, but it should transmit data to the head node. If this backward transmission is frequent (in fact, about 1/2 of the possibility), it must result in a waste of energy.

This work [108] proposes a communication protocol that uses forward transmission area according to the position of sink and the final data flow direction. In Figure 5.3, the arc of □$_1$ ruled out the possibility of node *i*'s backward transmission, which ensure that there will be no loops. □$_2$ contains all of the nodes that directly connected with node *i*. As an area that satisfy the two requirements, FTA(*i*) is the overlap section of the two circles, which contains all of the possible next nodes under topology and routing algorithm of this work.

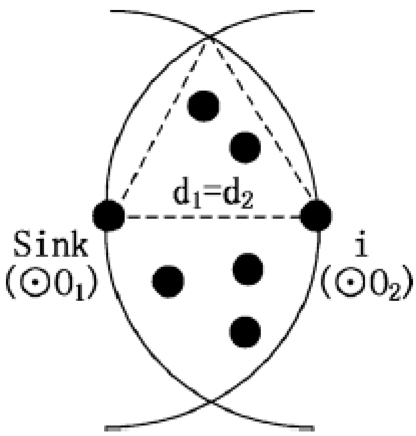

Figure 5.4: Minimum area of FTA(i).

Theorem 1: Based on (5.3.2.2), the area of *FTA(i)* is S_{FTA} *(i)* and is given by

$$\left(\frac{2}{3}\pi-\frac{\sqrt{3}}{2}\right)\left[\max d_{ij}\right]^2 \le S_{FTA}(i) < \frac{1}{2}\pi\left[\max\left(d_{ij}\right)\right]^2 \qquad (5.20)$$

Proof: In fact, $d(i, Sink) = d_1$, $d_{ip} = max(d_{ij}) = d_2$, the area of sector D_1 is S_1, the area of arch D_2 is S_2, and here D is a symbol of sector. According to the Cosine Theorem, we have

$$\theta = \arccos\left[1-\frac{1}{2}\left(\frac{d_2}{d_1}\right)^2\right] \tag{5.21}$$

According to Helen Theorem, we have

$$S_{\Delta iqSink} = \frac{1}{2}d_2\sqrt{d_1^2-\frac{1}{4}d_2^2} \tag{5.22}$$

Thus

$$S_1 = \frac{1}{4}d_2^2(\pi-\theta) \tag{5.23}$$

$$S_2 = \frac{1}{2}d_1^2\theta - S_{\Delta iqSink} \tag{5.24}$$

$$S_{FTA}(i) = 2(S_1+S_2) \tag{5.25}$$

$$S_{FTA}(i) = \frac{1}{2}\pi d_2^2 - d_2\sqrt{d_1^2-\frac{1}{4}d_2^2} + \left(d_1^2-\frac{1}{2}d_2^2\right)\times\arccos\left[1-\frac{1}{2}\left(\frac{d_2}{d_1}\right)^2\right] \tag{5.26}$$

Case 1: As shown in Figure 5.4, if the sink is a neighbour of node *i*, sink will be the furthest neighbour it is the final information source of the whole network. Thus, $d_1 = d_2$, according to (5.18), and the minimum area of FTA(*i*) is ($\left(2\pi/3-\sqrt{3}/2\right)d_2^2$.

Case 2: As shown in Figure 5.5, if d_1 tends to infinity, the maximum area of FTA(*i*) is $\pi d_2^2/2$. When the radius of □$_1$ is infinity, its arc that passes the centre of □$_2$ tends to be straight line, approximately dividing □$_2$ equally. Thus, the limitation of FTA(*i*) can be half the area of □$_2$. Theorem 1 is proven.

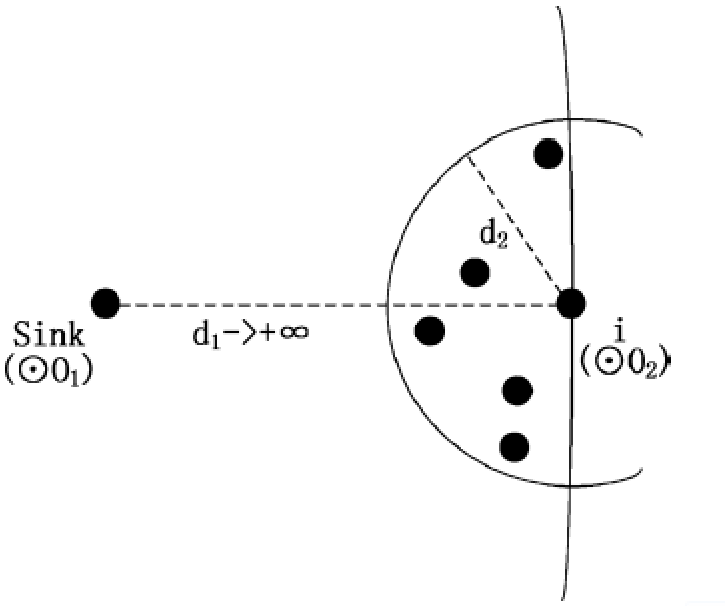

Figure 5.5: Maximum area of FTA(i)

Lemma 1: The area of FTA(i) fulfils the inequality

$$0 < S_{FTA}(i) < \frac{1}{2}\pi d_0^2 \tag{5.27}$$

where d_0 is the communication radial limitation of the normal sensor nodes.

Proof: When node i is infinitely close to Sink, d_2 approximately equals 0, so the minimum of FTA(i) tends to 0 but does not equal 0. When the distance is infinity, the communication radius of node i is the limitation d_0. The maximum of FTA (i) tends to be $\pi d_0^2/2$. Lemma 1 is proven.

Definition 5: The node's forward energy density FED (i, t) fulfils the equality

$$FED(i,t) = \frac{\sum_{j \in FTA(i)} E_j(t)}{S_{FTA}(i)} \tag{5.28}$$

where $E_j(t)$ is the energy value of node *j* at time *t* and $\sum_{j \in FTA(i)} E_j(t)$ is all of the neighbours' energy combined in function FTA (*i*).

Lemma 2: When $t = 0$, FED (*i*, *t*) fulfils the inequality:

$$\frac{2E(t=0)}{\pi d_0^2} < FED(i,t) < +\infty \tag{5.29}$$

where E_i ($t = 0$) is the same energy value of all of the nodes at time 0.

Proof: In Figure 5.5, if node *i* has only one neighbour with distance d_0, FTA is defined by this neighbour. The area is maximum, and the whole energy is minimum (only one node's energy), so FED (*i*, *t*) is minimum. When node *i* is infinitely close to Sink, $S_{FTA}(i)$ tends to 0, so FED (*i*, *t*) is maximum and tends to infinity. Lemma 2 is proven.

Definition 6: The forward-aware factor of the communication link between node *i* and node *j*, FTA (*ij*) is given by

$$FAF(ij) = \alpha \frac{FED(j)}{\sum_{j \in FTA(i)} FED(j)} + \beta \frac{w_{ij}}{\sum_{j \in FTA(i)} w_{ij}} \tag{5.30}$$

where $\sum_{j \in FTA(i)} FED(j)$ is all of the neighbours' FAF combined in FTA (*i*). The weight of edge (w_{ij}) is defined as (5.24). $\sum_{j \in FTA(i)} w_{ij}$ is all of the link weights combined that *i* has in FTA, α and β are positive harmonic coefficients, and

$$\alpha + \beta = 1 \tag{5.31}$$

5.3.3. Design of the FAF-EBRM

FAF-EBRM is mainly used for the large-scale WSN for static data collection and event detection. In equation 5.28, the first term takes the FED of all of the possible next-hop nodes into account, which means the ability to transmit data. The second term considers the weight of transmit link, which can be used to choose the next-hop node directly, Because the definition of the weight of edge in equation 5.3.2.13 considers parameters like nodes' energy, length, and load, the routing algorithm based on FAF is able to consider many factors and get a better energy-balanced solution.

Table 5.1: Routing Parameters of Nodes

Field Name	Significance
Neighbor_ID	Unique ID of each neighbor
Energy_ID	Energy ID of each neighbor
Distance_ID	Distance ID of each neighbor
FED_ID	FED ID of each neighbor

The routing algorithm can be divided into following stages.

1) Determine FTA (i) and all of the possible next-hop nodes of the node i. First, take d_0 as the communication radius, determine the set of all of the nodes that have edges with i, $N'(i)$. Select the nodes that closer to Sink than i does, which constitute the set of all of the possible next-hop nodes and the furthest node determine FTA (i).
2) Determine FTA (j) and $S_{FTA}(j)$ of each possible next-hop node. Determine FTA (j) as we determined FTA (i). Plug the furthest distance between j and nodes in FTA and the distance between j and *Sink* into (5.26) and obtain $S_{FTA}(j)$.
3) Calculate FED (j) of each possible next-hop node. Plug all of the nodes' energy into (5.29) and get FED (j).
4) Calculate the weight of edges between i and each nodes according to (5.16)
5) Plug the parameters of 3) and 4) into (5.30) and calculate FAF of each possible transmit link. Choose the next-hop node according to

$$j = \max_{j}\left[FAF\left(ij\right)\right] \tag{5.32}$$

6) If there is no node closer to Sink than i and $N'(i)$, directly compare FAF of all of the nodes in $N'(i)$, and choose the next-hop node according to (5.31).

7) If there is no node in *N'*(*i*), *i* will increase the transmit power to get a longer radius that d_0 until connected with another node, or *i* will abandon the packet.
8) If Sink is among the forward transmit nodes, *i* will transmit data directly to *Sink* and accomplish the procedure.

In FAF-EBRM, the routing list structure of nodes are shown in Table 5.1. The information of the table can guarantee all of the parameters FAF-EBRM algorithm needed. The communication launch node can calculate the weight of edge between neighbours. Neighbours can get its own FED. It avoids the communication launch node doing all of the algorithms. Thus, each node's memory should storage its own ID, real time energy, distance to the Sink, and FED at any moment, which could be feed back to launch node quickly.

5.3.4 Local Topology Reconfiguration Mechanism

In an actual routing procedure, nodes with greater signal strength will have more communication link and result in faster energy consumption. The whole network cannot always work under these topology structures. A topology reconnecting mechanism of the cluster head rotation algorithm like LEACH is needed. The whole WSN information is limited, and global topology change may affect the information perception, the global change caused by energy unbalanced area is a waste of energy to energy balanced area, so a local topology reconfiguration mechanism is necessary. Some researchers has proposes a point strength-driven local topology reconfiguration mechanism based on FAF-EBRM.

The stages of the algorithm as given here.

1) In FAF-EBRM, every time node *i* finishes transmission, check the point strength of the next-hop node *j*. If it is less than the average value of all of the sensors' strengths in FTA, the local topology reconfiguration mechanism should be launched in node *i's* FTA.
2) Before the topology reconfiguration mechanism is launched, remove the link

between *i* and *j*, remove *j* from FTA (*i*), and get a new set FTA'(*i*). Then, reconnect in FTA'(*i*), and function of connect possibility is given as

$$p_{i \to j} = s_j \Big/ \sum_{j \in FTA'(i)} s_j \tag{5.33}$$

3) The node removed in 2) may be the possible next-hop node when the next transmission is finished, and the revocation of the edge does not affect the possible reconnection. The node's real-time strength is needed to calculate the sum of strengths.

5.4 Performance Evaluation:

The simulation of this clustering routing scheme is done in ns2. In the simulation model, there are 40 sensor nodes are used here. All the nodes are set as static nodes. The type of the wireless propagation model is TwoRayGround. Routing protocol which is used in this simulation is AODV. Table 5.2 shows the various parameters used for simulation.

Table 5.2: Simulation Parameters

```
#====================================
#     Simulation parameters setup
#====================================
set NS          /home/Project/Desktop/leach/ns-allinone-2.34/ns-2.34/
set val(chan)   Channel/WirelessChannel    ;# channel type
set val(prop)   Propagation/TwoRayGround   ;# radio-propagation model
set val(netif)  Phy/WirelessPhy            ;# network interface type
set val(mac)    Mac/802_11                 ;# MAC type
set val(ifq)    Queue/DropTail/PriQueue    ;# interface queue type
set val(ll)     LL                         ;# link layer type
set val(ant)    Antenna/OmniAntenna        ;# antenna model
set val(ifqlen) 50                         ;# max packet in ifq
set val(nn)     40                         ;# number of mobilenodes
set val(rp)     BEC                        ;# routing protocol
set val(x)      1407                       ;# X dimension of topography
set val(y)      732                        ;# Y dimension of topography
set val(stop)   30.0                       ;# time of simulation end
set val(em)     EnergyModel                ;# energy model
set val(Energy) 1000                       ;#Joules
set speed       0.5                        ;#
set packet_size 811                        ;#
```

```
set interval .05                              ;#
#====================================
```

Table 5.3: Simulation Results BEC

Time(Sec)	Energy Values	Latency Values	PDR Values	Residual Energy Values
10.000	18.562	24.8182	0.9608	38981.1
15.000	35.123	24.8827	0.9756	38964.9
20.000	51.683	25.4729	0.9822	38948.3
25.000	68.253	25.4771	0.9861	38931.7
30.000	84.820	25.4303	0.9878	38915.2

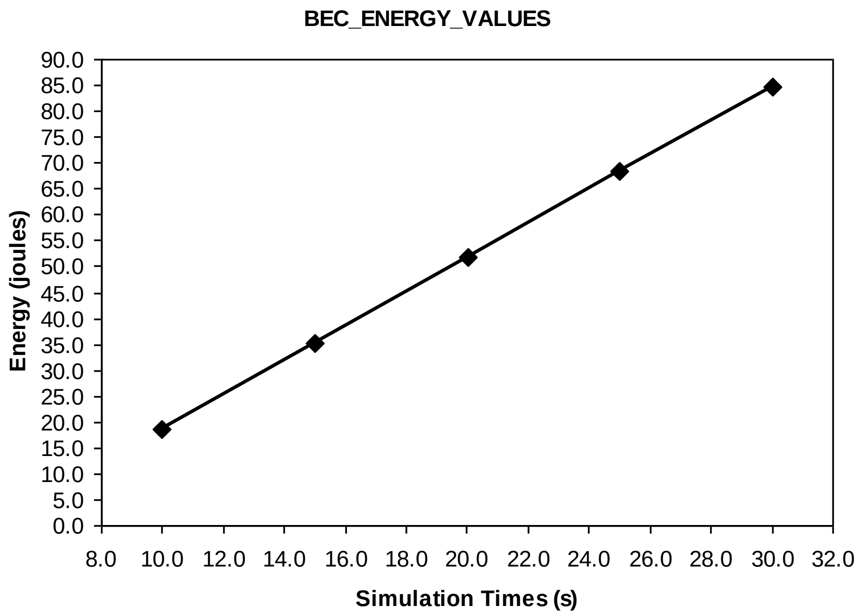

Figure 5.6: Simulation Time Vs Energy Values

The Energy Consumption Value at 10 sec Simulation Time is observed to be 18.562 for Energy-Balanced Routing Algorithm, at 15 sec, 20 sec, 25 sec, 30 sec are 35.123, 51.683, 68.253, 84.820 respectively. So it is clearly shown in Figure 5.6 that the variation of Energy Values with simulation time is increasing.

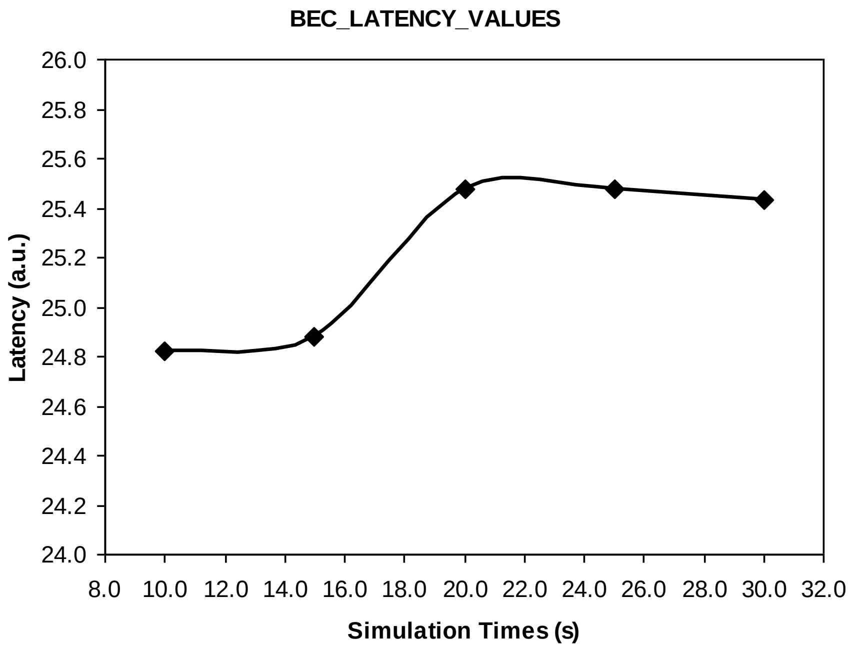

Figure 5.7: Simulation Time Vs Latency Values

Form the Figure 5.7 it is shown that the Latency Value at 10 sec Simulation Time is 24.8182. Then at 15 sec, 20 sec, 25 sec and 30 sec are observed to be 24.8827, 25.4729, 25.4771, and 25.4303 respectively. So from the above results we can say that the variation of Latency Values with Simulation Time is increasing.

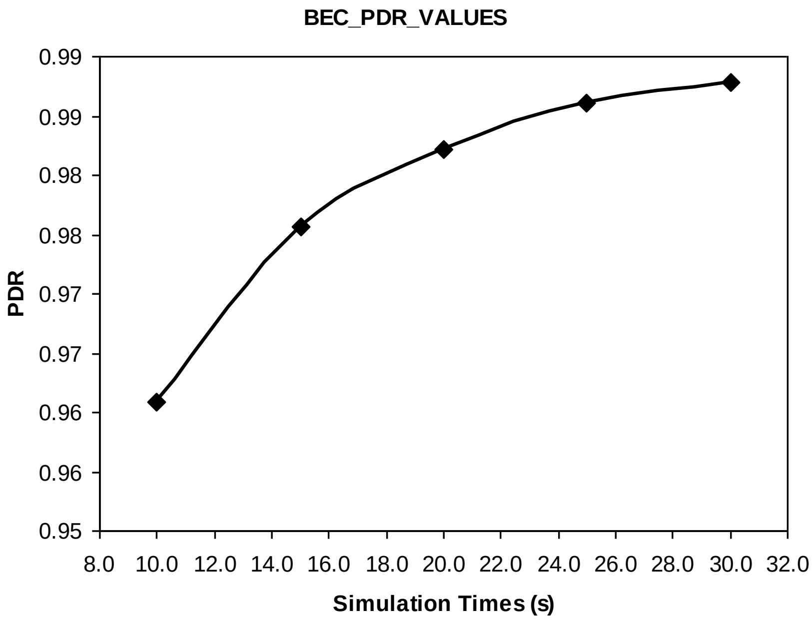

Figure 5.8: Simulation Time Vs PDR Values

Figure 5.8 shows the variation of Packet Delivery Ratio (PDR) values with simulation time from 10 sec to 30 sec at an interval of 5 sec. The PDR values are observed to be 0.9608, 0.9756, 0.9822, 0.9861 and 0.9878 respectively.

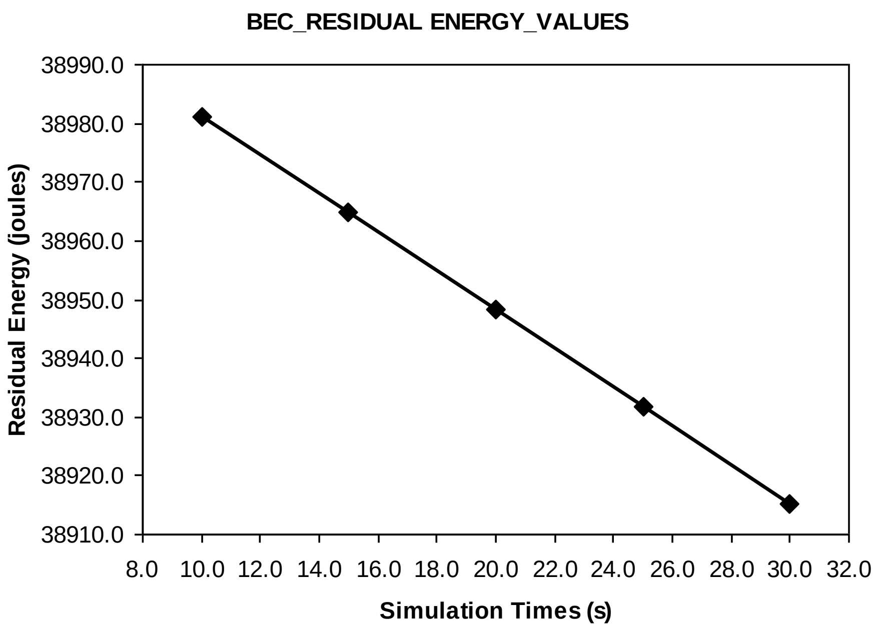

Figure 5.9: Simulation Time Vs Residual Energy Values

The Residual Energy Values at 10 sec Simulation Time is observed to be 38981.1 for BEC, at 15 sec, 20 sec, 25 sec, 30 sec are 38964.9, 38948.3, 38931.7, 38915.2 respectively.

5.5 Conclusions:

The present simulation work represents the variation of different performance parameters for the Energy Balanced Routing Scheme. Efficiently use of energy in the network has been the main issue in WSNs for prolonging lifetime of the network. This graph shows the Energy values, Latency values, Packet Delivery Ratio and Residual Energy Values using this algorithm.