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RESEARCH ARTICLE

Machine Learning

Fuzzy based congestion detection and control algorithm for energy efficient wireless sensor network (WSN)

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Abstract: A wireless sensor network (WSN) is built by numerous tiny, resource aware sensor nodes to facilitate and develop various fields such as the military, health care, disaster management etc. One of the major design issues in WSN is congestion detection and control. Data collision, channel contention, and buffer overflow are considered to be a few important factors that may lead to a congestion problem. Congestion causes increase in packet drop rate and thus network efficiency is decreased. Hence, the network performance and quality of service may be degraded. Therefore congestion detection and control are vital and critical challenges to be addressed. In this paper, a novel energy efficient fuzzy based congestion detection and control algorithm (EE-FBCDCA) has been proposed with the objective of addressing the energy aware congestion detection and control mechanism. The proposed work consists of three phases, namely, 1) Fuzzy inference system based congestion detection, 2) Congestion notification phase and 3) Fuzzy inference system based congestion control. In this work, once the congestion is detected and upon receiving the notification message, the intermediate nodes will adjust their respective transmission rate to prevent further drop of packets. Thus, EE- FBCDCA detects and control the congestion more effectively to improve the QoS of the network. The proposed work is implemented and analysed by using MATLAB, and the performance is compared with the existing HTCCFL and FBACC. The simulation results of EE-FBCDCA shows enhanced network lifetime, energy efficiency, and reliability.

Keywords: Congestion detection, control, fuzzy inference system, energy, network lifetime, WSN.

INTRODUCTION

A wireless sensor network (WSN) consists of numerous tiny sensor nodes deployed over a vast geographical area with limited resources such as energy and bandwidth availability (Bhushan & Sahoo, 2010; Banimelhem & Khasawneh, 2012; Antoniou *et al*., 2013; Chen *et al*., 2016; Rao & Rama Rao, 2022). In today's era, WSNs have wide applications in various fields, namely healthcare systems, military, multimedia etc. The sensor nodes are capable of collecting, processing and transmitting the data through the intermediate nodes to reach the sink nodes (Farzaneh & Yaghmaee, 2015). In WSN many design issues such as queuing delay, packet drop, packet collision, and congestion need to be addressed. Among all the above stated issues, one of the major problems in WSN is congestion, which needs to be addressed to enhance the network lifetime and performance. Congestion leads to numerous issues especially inefficient energy consumption by nodes, buffer overflow, and high packet loss (Gholipour *et al*., 2015). Thus, this problem will degrade the network performance and quality of service. The primary working principle of nodes is to sense, gather, process, and transmit the data to the sink nodes for analysis and decision making. In WSN, each node transmits the gathered data to the sink node for processing. Thus, vast amounts of data are forwarded towards the base station at

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any given instant of time, leading to network congestion and packet loss. As WSN play a vital role in various real time application domains, congestion will jeopardize the network lifetime and performance that need to be avoided (Jan *et al*., 2014). Thus, congestion is considered as a very important design challenge. Hence, it becomes essential to implement an efficient and reliable congestion control mechanism to address the problem (Sonmez *et al*., 2014).

and therefore energy is considered to be one of the major performance metrics during congestion detection (Uthra & Raja, 2014). Much research has been done towards the enhancement of energy conservation to prevent packet collision and congestion (Wang *et al*., 2012). But one of the major drawbacks in all this work is that energy consumption is not equally distributed among all the nodes (Ahmed *et al*., 2014; Yi & Yang, 2016; Zou & Qian, 2019). Different mechanisms and schemes were utilized by various researchers towards congestion detection and control process. Moreover, many research projects are focused towards fuzzy based congestion control and detection mechanisms (Munir & Man, 2007; Jutan *et al.,* 2012; Rekha & Gomathy, 2012). Therefore, designing a novel energy efficient congestion detection and control process with a better solution is considered as a major research challenge. In this work, a novel fuzzy based energy aware congestion detection and control algorithm for WSN has been proposed. This algorithm yields a better solution for congestion detection and control when compared to other existing algorithms.

The primary focus of the proposed work is to develop an energy aware, high reliable congestion detection and control algorithm for WSN. The proposed algorithm consists of three phases. The first phase is defined as a novel fuzzy based energy aware congestion detection phase with fuzzy input variables, such as packet delivery rate, residual energy level, and queue occupancy, with the aim of performing the task of congestion detection to enhance the energy efficiency of the network.

The next phase, the congestion notification phase, will be triggered to transmit the congestion signal to the nodes whenever congestion occurs in the network. Finally, in the third phase, *i.e.*, the fuzzy based congestion control phase, the data transmission rate of the nodes is controlled to prevent further congestion in the network. Thus, the proposed work ensures energy efficient, high throughput, minimal end-to-end delay, a smaller packet drop rate, and overall enhancement in the network performance.

Much research has been carried out in the field of congestion detection and controls in WSN (Misra *et al.,* 2009; Jenolin *et al*., 2011; Jan *et al*., 2014; Mahdizadeh *et al.,* 2014; Ghanavati *et al*., 2015). Ghaffari (2015) and Rekha Chakravarthi *et al.* (2010) have carried out comparative surveys on the congestion control algorithm. Congestion control (Chen & Zhang, 2006) is defined as a technique of controlling the amount of data flow in the network without any loss of information (Rezaee *et al.*, 2014). It consists of three primary phases namely detection (Chen & Yang, 2006), notification (Wan *et al.,* 2011), and control (Yin, 2009).

Ahmed & Paulus (2017) developed congestion avoidance and mitigation for multipath routing and load balancing in WSN. Cao *et al.* (2012) proposed a novel delay based congestion control for a multipath TCP feedback congestion control protocol. The experimental results of this protocol shows better energy and throughput.

Huang *et al.* (2009) developed an FACC protocol to detect congestion based on the classification of the nodes adjacent to the source and adjacent to the base station. Tao and Yu (2010) presented an enhanced congestion detection and avoidance protocol for detecting congestion by using buffer threshold and buffer weight. This protocol supports a hop-by-hop congestion control scheme. Adjeroh & Yaghmaee (2008) presented a queue based congestion control protocol with priority support to congestion control by considering the queue length as the index of density degree. Thus, in this protocol the transmission rate is controlled depending upon the priority and density degree.

Basaran *et al.* (2010) developed a control of sensor queue (CONSEQ) protocol with the aim of detecting congestion by considering the queue length and data transmission among the one hop neighbouring nodes. Akyildiz *et al.* (2003) proposed an event-to-sink reliable transport protocol. In this protocol, the packet transmission rate to the sink node is observed and queue overflow is identified. The intermediate nodes will detect the presence of congestion in the network by referring to the congestion bit in the packet.

A fuzzy inference system can be utilized to implement the congestion detection and control scheme (Rezaee & Pasandideh 2017; Sangeetha *et al.,* 2019). Many fuzzy inference system based models have been proposed to address various issues in WSN (Logambigai & Kannan, 2016; Rajeswari *et al.,* 2019).

A fuzzy temporal congestion predication model was proposed to identify the congestion free path. This model consists of two phases, namely, congestion prediction and localization phases (Mukherjee & Dasgupta, 2013). Hatamian *et al.* (2016) developed a fuzzy rate controller based congestion aware routing by assigning priority to data packets. Ghanavati *et al.* *(*2013) presented a type 2 fuzzy logic algorithm to measure and control the congestion level, to enhance the QoS in WSN. This algorithm improves the network lifetime and decreases the packet drop rate.

Ghaffari (2014) proposed a star algorithm based routing mechanism to ensure improved link quality and reduced hop count. But in this method end-to-end delay is more and thus the complexity is greater. Sayyad and Choudhari (2014) proposed a Hierarchical Tree based congestion control using fuzzy logic (HTCCFL) using the following metrics, namely, packet service ratio, number of competitors, and buffer occupancy. The above algorithm gives increased energy efficiency by selecting an alternate path with less congestion for data transmission.

Hatamian and Barati (2015) developed a priority based congestion control schema using fuzzy rules in WSN. In this method, buffer occupancy and congestion level are considered as input parameter for a fuzzy rate controller to monitor the packet transmission rate. Damaso *et al.* (2014) proposed a reliable framework with energy as a primary constraint. Blocks and models were used to express the sensor reliability elements using the energy factor. Mostafaei (2019) proposed distributed learning automation (DLA) to identify the small group of nodes to enhance end to end reliability.

Ullah *et al.* (2017) proposed an energy and congestion aware routing for an AMI network in a smart city. In this method, residual energy and queue occupancy are considered as major factors monitoring and controlling the congestion level. Song *et al.* *(*2019) developed a unified modelling framework known as GLS for space terrestrial networks. Jaiswal and Yadav (2013) developed a fuzzy based adaptive congestion control (FBACC) that enable congestion estimation by considering the factors buffer occupancy and traffic rate. FBACC enhances the energy efficiency and reduces the packet drop rate.

Gharajeh and Khanmohammadi (2016) developed DFRTP based upon the distance and numbers of neighbouring nodes, which were considered as the input parameters. DFRTP yields better network lifetime and packet drop rate. Chen *et al.* (2015) developed a RLAN to detect the node position under varying magnitude across various directions. Khan *et al.* (2020) proposed and implemented the ant colony optimization Technique and repetitive route configuration with reactive routing protocol for obstruction of Black Hole Attack in mobile *ad hoc* networks. Perumal and Subramaniyan (2020) developed the statistical Markov model based natural inspired glow worm multi-objective optimization (SMM-NIGMO) technique for Energy efficient data delivery in MANET.

In spite of the availability of much related work in the literature survey, an energy efficient congestion detection and control in WSN still remains as a major design goal, following the metrics buffer size, service time, and channel load. These studies do not focus much on energy efficiency based congestion detection and control process. Hence there is a need to design an energy efficient congestion detection and control algorithm for WSN for enhancing the throughput, reducing delay, and increasing energy efficiency and reliability. This novel challenge is addressed in this work. Moreover, most of the related work focuses on Energy Efficient Fuzzy Based Congestion Detection and Control Algorithm, and This work is proposed with the objective of improving the network performance and lifetime.

The rest of this paper is structured as follows. Section 2 describes in detail the Proposed Methodology. Section 3 illustrates and discusses the simulation based results. Section 4 finally concludes the paper.

MATERIALS AND METHODS

Energy efficient fuzzy based congestion detection and control algorithm (EE- FBCDCA)– energy model

The energy model considered in this proposed work, EE-FBCDCA, is similar to the work developed by Heinzelman and Balakrishnan (2002). According to the first order radio model, the amount of energy consumed during the transmission of a packet with 1 bit over d distance is given by the Equation (1). The E_{elec} indicates the amount of energy consumed per bit to run the transmitter or receiver circuitry. E_{fs} and E_{mp} are the amplifier energies in free space and multipath, respectively.

$$E_{Tran}(L) = \begin{Bmatrix} LE_{elec} + L\varepsilon_{fs}d^2 for d < d_0 \\ LE_{elec} + L\varepsilon_{mp}d^4 for d > d_0 \end{Bmatrix} \qquad ...(1)$$

$$where\ d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}}$$

The energy $E_{RX}(l)$, which indicates the amount of energy consumed in receiving a packet with 1 bit, is given by Equation (2).

$$E_{RX}(l) = E_{elec} \qquad ...(2)$$

EE-FBCDCA

An energy aware congestion control mechanism is considered to be a major design challenge for WSN. Hence in this work, a novel EE- FBCDCA based on a fuzzy inference system has been proposed with the objective of detecting and controlling the congestion. The residual energy level and reliability are considered as major aspects for measuring the network performance. In the proposed algorithm the network congestion is detected by considering the data flow from sources to base station. Moreover, buffer capacity is considered to be an important metric for the process of congestion monitoring and detection. The proposed work consists of the following three phases, namely i) Congestion Detection Phase, ii) Congestion Notification Phase, and iii) Congestion Control Phase. Figure 1 Shows the architecture of the proposed EE- FBCDCA.

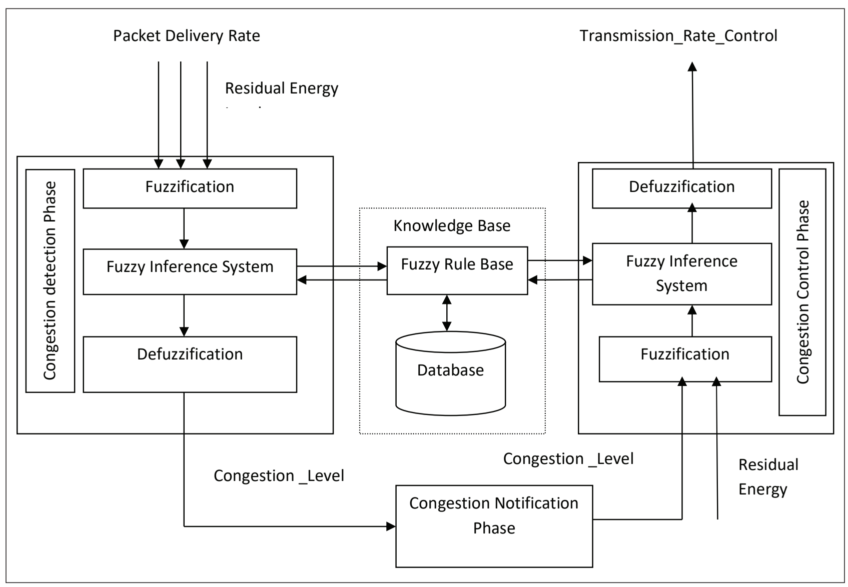

Figure 1: Architecture of the proposed EE- FBCDCA

Design of energy efficient fuzzy inference system for congestion control and detection Phases.

In this proposed work, the FIS is defined under the following two scenarios: firstly, for congestion detection phase and secondly, during the process of congestion control.

The fuzzy inference system (FIS) employed in this work consists of the following 4 main components:
(i) Fuzzifier
(ii) Fuzzy inference engine (FIE)
(iii) Fuzzy rule base, and
(iv) Defuzzifier.

Congestion detection and control are the most important design challenges in the WSN environment. Thus, to address these challenges an EE- FBCDCA is developed in this work. The major goal of the proposed work is address detection as well as controlling congestion in the network, in order to to improve the network reliability and lifetime. Thus, this section elaborates in detail the proposed work, EE- FBCDCA. The main flow of the proposed EE- FBCDCA is shown below in Algorithm 1.

The EE- FBCDCA has been proposed with the following two major objectives.

1. A novel energy aware fuzzy based congestion control scheme is proposed to prevent the congestion.

2. Energy conservation is improved by congestion control using the fuzzy rules. Hence, the network lifetime is enhanced.

The proposed EE- FBCDCA consists of the following three phases:
1. Fuzzy inference system based congestion detection phase
2. Congestion notification phase
3. Fuzzy inference system based congestion control phase

Algorithm 1 - EE- FBCDCA

Input : Senor Nodes
Output : Congestion Free Network Environment
For each Node n do
Random _number = rand(0,1)
If ($q_{len} < TH$) $then$
Congestion_Level = Fuzzy_logic1 (REL,PDR,Buffer_Capacity)
If ($Congestion\_Level < Random\_Number$)
Add Packet 'P' to the node's buffer
Else
Send Congestion_Warning_Signal (Node_ ID,REL) to its Neighbour Nodes
End If
For each Neighbour (M) on receiving the Congestion_ Warning_Signal
Transmission_Rate_Control = Fuzzy_logic_2 (Congestion_Level,REL)
End For
End if
End For

The following subsection describes each of the phases in detail.

Fuzzy inference system based congestion detection phase

In the proposed work, the fuzzy inference system is employed to detect the congestion level of the network. The main objective of this proposed work is to improve the network lifetime and performance by controlling and managing the transmission rate of the nodes, so that the congestion level will be reduced. The primary role of this phase is to detect the congestion level of every node in the network. Thus, in this phase, queue length is measured periodically to detect the traffic level in the network. Moreover, in this proposed work the fuzzy logic inference system is used for measuring the congestion level. The three fuzzy input variables used are Buffer Capacity, Residual Energy, and Packet Delivery Rate.

Description of the fuzzy variables

Buffer capacity

The buffer capacity of any node, say (n), is defined as the maximum amount of data packets that a node can store before processing. Thus, the buffer capacity parameter plays a vital role during the congestion detection scheme. The buffer capacity is measured by using Equation (3), given below:

$$Buffer\_Capacity = \frac{Buffer_{Size} - Buffer_{Packet}}{Buffer_{Size}} \quad ...(3)$$

where $Buffer_{Size}$ indicates the buffer size of a node, and $Buffer_{Packet}$ indicates the number of packets available in the buffer at given instant 't'.

Hence, if the $Buffer_{Packet}$ is zero, then it indicates that the node's buffer is empty, whereas if $Buffer_{Size}$ is equal *to* $Buffer_{Packet}$ it indicates that the buffer is full and thus all the arriving packets are dropped, which may lead to congestion in the network .

The threshold Buffer length (B_{TH}) is calculated by using Equation (4), given below:

$$B_{TH} = \frac{\mathrm{Packet}_{\mathrm{T}}^{\mathrm{N}}}{Buffer_{Size}} \quad ...(4)$$

where $\mathrm{Packet}_{\mathrm{T}}^{\mathrm{N}}$ is the amount of data packets arrived at node 'N' at given time 't'.

Packet delivery rate

The packet delivery rate at any node 'n' is estimated with respect to the packet service time at node 'n'. P_{ST} is defined as the time taken by the node for successfully transmission of a single packet over the communication path.

Thus, the packet average service time can be measured by considering an exponential weighted sum formula as shown below, Equation (5):

$$P_{ST} = (1 - \alpha)P_{ST} + \alpha P_{ST} \quad ...(5)$$

where α is constant such that $0 \leq \alpha \leq 1$

Thus, by using the measured P_{ST}, the node rate can be estimated by using Equation (6), given below:

$$PDR = \frac{1}{P_{ST}} \quad ...(6)$$

Residual energy level (REL)

The REL of a node is calculated by using Equation (7), given below:

$$\text{REL (N)} < E_{\text{thres}} \quad ...(7)$$

where REL (N) is the Residual Energy Level of the node N, and E_{thres} is the threshold energy. The threshold energy (E_{thres}) is calculated by using Equation (8).

$$E_{thres} = \frac{\sum_{i=1}^{N} REL_i}{N} \quad ...(8)$$

where REL is the Residual Energy Level, and N is the Number of nodes in the network.

Congestion in a network leads to packet drop or collision that may increase the retransmission of same set of data packets by node. Hence, the node's energy level drastically decreases. Thus, congestion acts as one of the primary source of decrease in network lifetime as well as energy efficiency. Table 1 shows the fuzzy rules for estimating the congestion level in the system.

The following parameters such as Buffer Length, Residual Energy Level, and Packet Delivery Rate are considered as fuzzy inputs whereas the Congestion Level act as fuzzy output. Thus, the fuzzy inputs variables and its linguistic variables used for Congestion Level estimation are shown below.

Buffer Length has the following linguistic variables, namely Low, Medium, and High. Residual Energy Level holds linguistics variables Low, Medium, and High, whereas the Packet Delivery Rate has the following linguistic variables, namely High_Flow, Medium_Flow, and Low_Flow. The output variable Congestion_Level has the following five linguistics variables: Low, Very Low, High, Very High and Medium.

Table 1: Fuzzy Rules for measuring the Congestion_Level

Set of "IF- THEN" Rules
Rule_I: IF Buffer_Length is High and Residual_Energy_Level is High and Packet_Delivery_Rate is High-Flow THEN Congestion_Level is High.
Rule_II :IF Buffer_Length is Low and Residual_Energy_Level is Low and Packet_Delivery_Rate is High_Flow THEN Congestion_Level is Low
Rule_III: IF Buffer_Length is Low and Residual_Energy_Level is Low and Packet_Delivery_Rate is High_Flow THEN Congestion_Level is Low.
Rule_IV: IF Buffer_Length is High and Residual_Energy_Level is Low and Packet_Delivery_Rate is Low_Flow THEN Congestion_Level is Very High.
Rule_V: IF Buffer_Length is Low and Residual_Energy_Level is High and Packet_Delivery_Rate is Low_Flow THEN Congestion_Level is Medium.

Congestion notification phase

Once the congestion is detected, in order to prevent the worst case of more packets begin transmitted over the network all other intermediate nodes should be notified about the congestion issue. Thus in this proposed work, through the congestion notification phase, the nodes are given a warning signal about the congestion in the network. In this phase, the congestion notification mechanism based on the ICN scheme of Yi *et al.*(2008) is employed. Thus, the nodes will transmit the piggyback packet holding the congestion warning signal. The main advantage of this phase is to prevent a network form getting more congested with additional control packets and in turn to enhance the network lifetime and energy efficiency.

Fuzzy inference system based congestion control phase

In this phase, we have developed a fuzzy based rate control scheme that will perform congestion control and prevent its subsequent issues in network such as delay in transmission, inefficient energy consumption, reduced network lifetime, etc. Moreover, the primary objective of this phase is to control the congestion by initiating the intermediate nodes to reduce its transmission rate once after receiving the congestion notification signal. Hence, this may leads to prevent further more congestion in network and enhance the network performance. Once again Fuzzy Inference System is utilized in this phases. Congestion Control phases is carried out by considering the following two metrics namely Congestion_Level and Residual Energy. Hence each node evaluates the Transmission_Rate_Control by using the fuzzy logic to determine the nodes probability to control the data transmission rate. Table 2 shows the fuzzy rules for evaluating the parameter Transmission_Rate_Control. The two fuzzy input variables and its corresponding linguistics variables for Transmission_Rate_Control are shown below.

Congestion_Level has the following linguistic variables, namely Low, Medium and High. The Residual_Energy_Level holds linguistic variables Low, Medium, and High. The output variable Transmission_Rate_Control has the linguistics variables Increase_Low, Increase_High and Decrease.

Table 2: Fuzzy Rules to evaluate the Transmission_Rate_Control

Set of "IF- THEN" Rules
Rule_I: IF Congestion_Level is Low and Residual_Energy_Level is Low and THEN Transmission_Rate_Control is Decrease.
Rule_II: IF Congestion_Level is Low and Residual_Energy_Level is Medium and THEN Transmission_Rate_Control is Increase.
Rule_III: IF Congestion_Level is Medium and Residual_Energy_Level is High and THEN Transmission_Rate_Control is Increase.

In our fuzzy inference system, the Congestion_Level and Transmission_Rate_Control are determined using both the triangular and trapezoidal membership functions. The triangular membership functions are used to represent the intermediate variables whereas for boundary variables the trapezoidal membership functions is used.

The triangular membership functions and trapezoidal membership functions (Rezaee *et al*., 2014) are calculated using Equation (9) and Equation (10), respectively.

$$A = \begin{Bmatrix} 0, x \leq a1 \\ \dfrac{x - a1}{b1 - a1}, a1 \leq x \leq \mathrm{b1} \\ \dfrac{\mathrm{c1 - x}}{\mathrm{c1 - b1}}, \quad \mathrm{b1 \leq x \leq c1} \\ 0, \quad \mathrm{x \leq a2} \end{Bmatrix} \qquad \text{...(9)}$$

$$A = \begin{Bmatrix} 0, x \leq a2 \\ \frac{x-a2}{b2-a2}, a2 \leq x \leq b2 \\ \frac{d2-x}{d2-c2}, c2 \leq x \leq d2 \\ 0, d2 \leq x \end{Bmatrix} \qquad \text{...(10)}$$

The finale step in FIS is the defuzzification. The primary objective of this step is to obtain the crisp output equivalent to the fuzzy output. Moreover, in this work we have used the Center of Area COA method for defuzzification. This is measured by using the Equation (11).

$$COA = \frac{\int \mu_A(x).xdx}{\int \mu_A(x)dx} \qquad \text{...(11)}$$

where $\mu_A(x)$ denotes the fuzzy values for the membership functions.

Illustration

In this section we have illustrated the fuzzy based congestion_level estimation mechanism in detail, with a suitable example.

For example, assume that the Packet_Delivery_Rate is 50, Buffer Length is 0.35 and Residual Energy Level (REL) is 0.9. Table 3 shows the fuzzy variables and their corresponding values. Table 4 shows the corresponding minimum and maximum values for the fuzzy variables.

The input value Z = 50 indicates the packet delivery rate of the node. Thus by setting the trapezoidal member function to low, we get

$$f(z;k,l,m,n) \quad = max\left(min\left(\frac{z-k}{l-k}, 1, \frac{n-z}{n-m}\right), 0\right)$$

$$f(162;70{,}135{,}162{,}165) = max\left(min\left(\frac{50-0}{1-0}, 1, \frac{65-50}{65-40}\right), 0\right)$$

$$= max(min(50{,}1{,}0.6), 0)$$

$$= max(0.6{,}0)$$

$$= 0.6$$

Similarly, by setting the triangular and trapezoidal member functions for buffer length to low and medium, respectively, we get, Z = 0.35 (Low)

$$f(z;k,l,m,n) \quad = max\left(min\left(\frac{z-k}{l-k},1,\frac{n-z}{n-m}\right),0\right)$$

$$f(162;70,135,162,165) \quad = max\left(min\left(\frac{0.35-0}{1-0},1,\frac{0.40-0.35}{0.40-0.30}\right),0\right)$$

$$= max(min(0.35,1,0.5),0)$$

$$= max(0.35,0)$$

$$= 0.35$$

Z = 0.35 (Medium)

$$f(z;k,l,m) = max\left(min\left(\frac{z-k}{l-k},\frac{m-z}{m-l}\right),0\right)$$

$$f(z;k,l,m) = max\left(min\left(\frac{0.35-0.25}{0.45-0.25},\frac{0.70-0.35}{0.70-0.45}\right),0\right)$$

$$= max(min(0.5,1.4),0)$$

$$= max(0.5,0)$$

$$= 0.5$$

Similarly, by setting the triangular and trapezoidal member functions for residual energy level to medium and high, respectively, we get,

Z = 0.9 (Medium)

$$f(z;k,l,m) = max\left(min\left(\frac{z-k}{l-k},\frac{m-z}{m-l}\right),0\right)$$

$$f(z;k,l,m) = max\left(min\left(\frac{0.9-0.1}{0.4-0.1},\frac{0.9-0.8}{0.9-0.4}\right),0\right)$$

$$= max(min(2.66,0.2),0)$$

$$= max(0.2,0)$$

$$= 0.2$$

Z = 0.9 (High)

$$f(z;k,l,m,n) \quad = max\left(min\left(\frac{z-k}{l-k},1,\frac{n-z}{n-m}\right),0\right)$$

$$f(z;k,l,m,n) \quad = max\left(min\left(\frac{0.9-0.4}{0.8-0.4},1,\frac{1.2-0.9}{1.2-1}\right),0\right)$$

$$= max(min(1.25,1,1.5),0)$$

$$= max(1,0)$$

$$= 1$$

Applying the obtained values in fuzzy rules 1 to 4,

$Rule\ 1: \min(0.6,0.35,0.2) = 0.2$

$Rule\ 2: \min(0.6,0.35,1) = 0.35$

$Rule\ 3: \min(0.6,0.5,0.2) = 0.2$

$Rule\ 4: \min(0.6,0.5,1) = 0.5$

The maximum value obtained from Rule 1 to Rule 4 is 0.5. Rule 4, corresponding to the maximum value, represents the medium probability of congestion_level in the node. The crisp value ranges from 0.25 to 0.7. During the defuzzification process, the corresponding values are substituted to obtain the value of the congestion_level as 0.61.

Table 3: Fuzzy variables and their input range

Fuzzy Input	Fuzzy variable	Input range
Packet_Delivery_Rate	Low	0-60
	Medium	55-170
	High	150-200
Buffer Length	Low	0-0.40
	Medium	0.25-0.70
	High	0.60-1
Energy	Low	0.0 – 0.5
	Medium	0.1 – 0.8
	High	0.5 – 1
Fuzzy Outputs	Fuzzy variable	Input Range
Congestion_Level	Low	0.01-0.05
	Medium	0.25-0.7
	High	0.5-1
Transmission_Rate_ Control	Increase_Low	0.01-0.06
	Increase_High	0.35-0.7
	Decrease	065-1

Table 4: Minimum and maximum value for fuzzy variables

Fuzzy variables	Minimum crisp value	Maximum crisp value
Packet_Delivery _Rate	0	200
Buffer Length	0	1
Energy	0	1
Congestion_Level	0.01	1
Transmission_Rate_Control	0	1

RESULTS AND DISCUSSION

The proposed work has been tested using MATLAB software because the MATLAB fuzzy tool box consists of all the fuzzy membership functions. Hence, MATLAB is the most efficient and convenient software to carry out the experiments of the proposed work EE- FBCDCA. The experiment were carried out with different nodes, starting from 100 nodes up to 200, deployed over network area of (500 x 500) m^2. The simulation parameters are listed in Table 5.

Table 5: Simulation parameters

Parameters	Value
Simulation Area	500 m x 500 m
Number of Nodes	200 Nodes
Initial Node Energy	0.5 J
Packet Size	512 Bytes

Packet delivery rate

Figure 2 shows the packet delivery rate of proposed algorithm, and it is compared with other existing algorithms. From Figure 2, it is observed that the packet delivery rate of EE- FBCDCA is greater when compared to other existing work. This is because, in the proposed work, the congestion control phase is initiated to control the packet transmission rate of the intermediate nodes, to control the congestion level in the network. Thus, in EE- FBCDCA congestion control phases play a vital role to control the packet loss ratio and hence the network efficiency is enhanced.

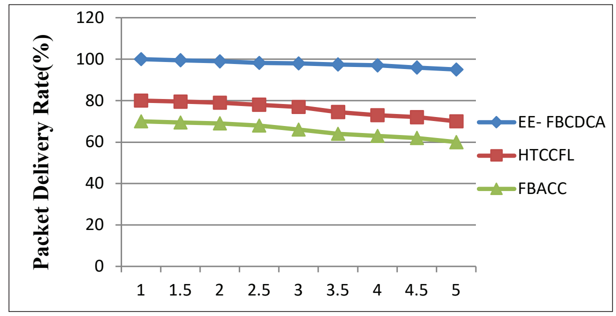

Figure 2: Packet delivery rate

Network lifetime

Figure 3 illustrates the network lifetime comparative analysis of the EE- FBCDCA and other existing algorithms. From Figure 3, it is observed that the proposed work shows better network life than other algorithms. This is because, in the proposed work, once congestion is detected, the packet forwarding rate of the nodes in the network is reduced. This may prevent furthermore congestion and loss of data in the network. Thus, EE- FBCDCA enhances the network lifetime and improves the performance of the network.

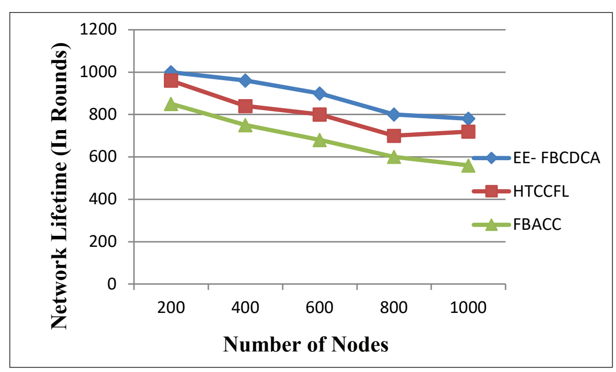

Figure 3: Network lifetime

Reliability

Figure 4 depicts the reliability comparison between the EE-FBCDCA and other existing algorithms. Reliability is the network parameter that estimates the network lifetime for a given period of time, say 't'. From

Figure 4 it is observed that the proposed algorithm gives a high reliability rate when compared with other existing algorithms. This is because in EE- FBCDCA, further congestion will be avoided by activating the congestion notification phase and hence the packet drop in the network will be prevented. Therefore the reliability rate is improved in the proposed work and network performance is enhanced.

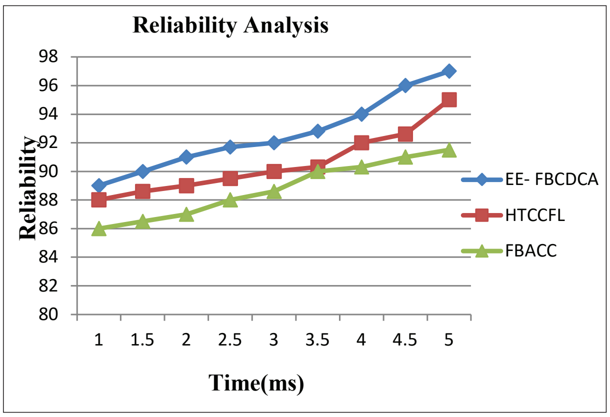

Figure 4: Reliability

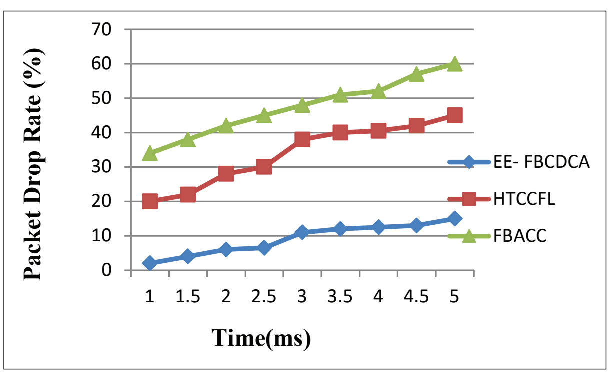

Figure 5: Packet drop rate

Packet drop rate

Figure 5 illustrate the comparative analysis of the packet drop rate of the EE-FBCDCA and other existing algorithms. The packet drop rate is measured by considering the formula given below, Equation (12).

$$PacketDropRate = \frac{P_\alpha}{P_\alpha + P_\beta} \quad ...(12)$$

Where P_α *represents the number of packets dropped* by a node

P_β *represents the number of packets received* by a node

From Figure 5 it is observed that the packet drop probability of the proposed work is less than the that of other existing algorithms. This is because in the proposed algorithm, both the fuzzy based congestion detection and control phases ensure reduced packet loss rate. Thus, the proposed work yields improved network lifetime with decreased packet drop rate.

Delay

Figure 6 shows the comparative analysis of delay of the EE-FBCDCA with the existing algorithms. End to end delay is defined as the average time taken by the packet to reach the destination node successfully. Thus, minimal delay indicates a better performance of the network. From Figure 6 it is observed that the delay of the proposed work is less than that of the other existing algorithms. This is because the EE-FBCDCA algorithm contains a very efficient congestion control process that may lead to reduced delay in the network.

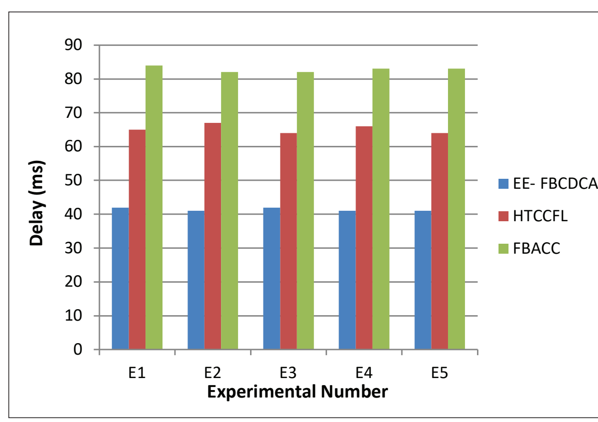

Figure 6: Delay

Energy consumption

Figure 7 depicts the average energy consumption per bit comparative analysis of the EE- FBCDCA and other existing algorithms. The average energy consumption per bit is defined to be the energy required to transmit a data packet successfully from the source to the destination.

From Figure 7, it is clear that the proposed work consumes less energy than existing algorithms. This is because the EE-FBCDCA uses fuzzy based congestion control phases that reduce the amount of data transmitted by the intermediate nodes. Since the congestion is controlled to greater extent that may lead to reduce the data drop rate and therefore energy conservation is improved.

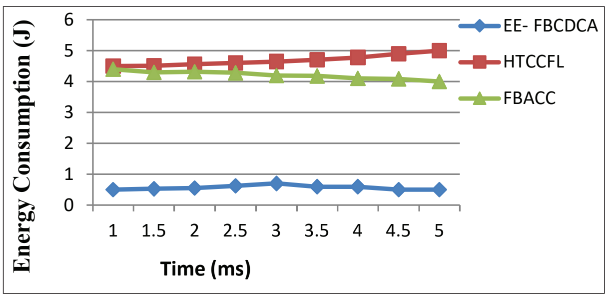

Figure 7: Energy consumption

Throughput

Figure 8 shows the throughput analysis of the proposed work and other existing algorithms. The experiments are conducted for a varying number of nodes, from 200 to 1000. From Figure 8 it is observed that network throughput increases continuously with an increase in the number of nodes. The throughput in the proposed work is improved by applying a fuzzy based congestion detection and control phase that reduces the packet loss rate. Hence, in EE- FBCDCA the number of data packets that are transmitted successfully is more, and in turn network throughput is improved to a greater extent.

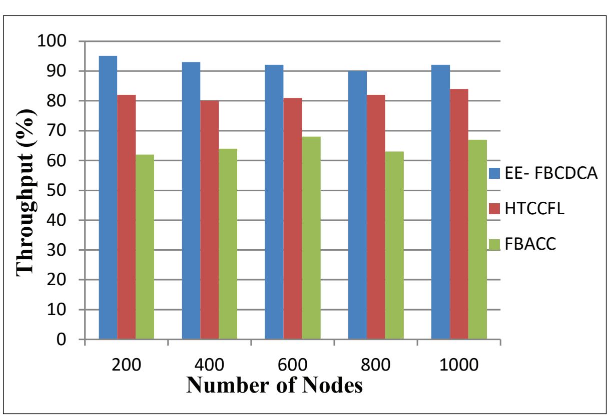

Figure 8: Throughput

Residual energy

Figure 9 depicts the residual energy analysis of the EE-FBCDCA algorithm with other existing algorithms. From Figure 9 it is clear that the proposed work gives more residual energy than other algorithms. This is due to the fuzzy based congestion detection process utilized in the proposed work. Hence the packet drop rate is reduced, and so, more energy is conserved. Therefore, the proposed work gives high residual energy.

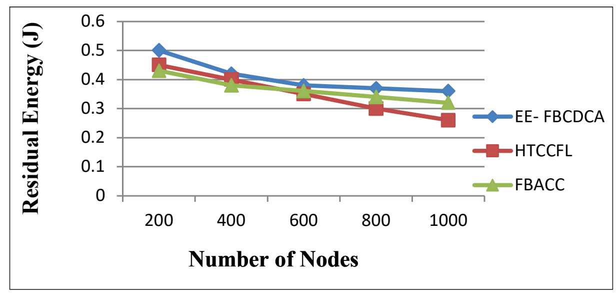

Figure 9: Residual energy

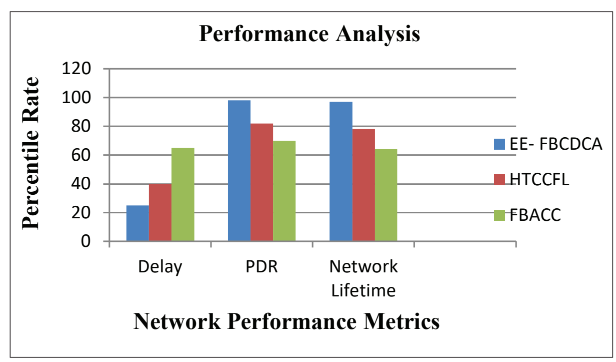

Figure 10: Network performance analysis

Network performance analysis

Figure 10 depicts the network performance analysis of the EE-FBCDCA algorithm and other two existing algorithms. From Figure 10 it is clear that the EE-FBCDCA algorithm gives better network performance in terms of the metrics Packet Delivery Rate (PDR), Delay, and Network Lifetime.

CONCLUSION

In this paper, a novel energy efficient fuzzy based congestion detection and control algorithm has been proposed with the objective of detecting and controlling congestion in WSN for enhancing the energy efficiency and lifetime of the network. Moreover, fuzzy rules are used in the process of both detection and control of congestion. Through simulation results using MATLAB, the proposed algorithm is evaluated and it has been proved that EE- FBCDCA shows better results when compared to the existing traditional processes, such as HTCCFL and FBACC, in terms of network lifetime, stability and overall performance. Thus, from the simulation results it is observed that the proposed process, EE-FBCDCA, outperforms the other existing processes in improving the lifetime of the network by 35%. Similarly, EE-FBCDCA shows 30% - 33%, and 35% - 38% better throughput in comparison to HTCCFL and FBACC, respectively. Moreover, from the proposed work, it is observed that above 78% of the residual energy in the network is sustained, which enables the transmission of data with reduced delay. Finally, from the experiments conducted it has been proved the proposed algorithm, EE-FBCDCA, gives better congestion detection and control and reduced end to end delay, as well as increased throughput, energy efficiency, and reliability.

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