SSRG International Journal of Electronics and Communication Engineering
ISSN: 2348-8549 / https://doi.org/10.14445/23488549/IJECE-V10I4P107
Volume 10 Issue 4, 63-70, April 2023

Original Article

Improving the Performance of Routing Protocols in MANETs: A Mathematical Model for Evaluating Intermediate Bottleneck Nodes

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Received: 03 March 2023 Revised: 08 April 2023 Accepted: 17 April 2023 Published: 30 April 2023

Abstract *- This study analyses an intermediate bottleneck node's performance using a random poison process mathematical model to solve Mobile Ad-Hoc Networks (MANETs') battery life problem. The goal is to make routing protocols in MANETs work better by dealing with the problem of bottleneck nodes and reducing packet loss. In MANETs, a bottleneck node is a node that has to forward packets from multiple sources, which causes packet loss. This paper gives a mathematical model for figuring out how well intermediate bottleneck nodes in MANETs work by figuring out the average length of the queue at the input buffer and the average delay time in the buffer. This evaluation tells if a node will become a bottleneck. This evaluation also decides whether or not the node should be added to the route. So, this model is used to make routing protocols in MANETs work better by getting rid of the problem of bottleneck nodes and cutting down on packet loss.*

Keywords *- Intermediate bottleneck node, Random poison process, Mathematical model, Mobile Ad-Hoc Networks (MANETs), Battery life, Routing protocols, Packet loss, Average length of queue, and Average delay time.*

1. Introduction

Infrastructure-based and infrastructure-less communication are the two most common network communication models in wireless communication. As part of an infrastructure-based communication system, a wireless connection facilitates communication between Mobile and fixed nodes. Because mobile nodes interact with static nodes within their radio range, this architecture necessitates a fixed, permanent infrastructure. On the other hand, infrastructure-less communication is a network model that does not require infrastructure and consists of mobile nodes that form a dynamic, transient, and self-formed network. It is possible to communicate between mobile nodes using either a single hop or multiple hops to transmit information through intermediary nodes. This concept, which functions as a multi-hop peer-to-peer packet radio network, is called a Mobile Ad hoc Network [1-19].

MANETs are made up of mobile nodes that are both diverse and capable of organizing themselves. They connect through intermediary nodes, which constitute a network consisting of many hops. Every network node functions as a host and router, sending data packets to the subsequent hop. While considering mobility, essential characteristics in the MANET environment include the hop count and the radio range of the MNs.

In recent years, researchers' attention has been drawn to MANETs because of these qualities, and as a result, a significant number of protocols for routing have been established. Depending on their nature, these procedures can be reactive [32], proactive, or hybrid. Proactive protocols construct pathways between the source and the destination regardless of whether or not this is necessary [22]. Routes are only established by reactive protocols when required [1-19]. Since dissimilar mobile devices are supplied with restricted power batteries, energy efficiency is one of the most important design considerations for MANETs. Not only is it necessary for routing protocols to consider the amount of energy used during the end-to-end trip of packets, but they must also enable reliable routing over the connections and use the remaining energy of nodes [21]. The purpose of the routing protocol is to increase the network lifetime while simultaneously lowering the amount of energy spent on data communication while also improving the Quality of Service [24].

This study proposes an analytical model for analyzing the performance of an intermediate bottleneck node.

Through the implementation of a random poison process [24-31]. The method calculates the typical queue length at the input buffer and the typical amount of time spent waiting in the buffer. The model is applied to exercise control over an intermediate node's incoming traffic and determine whether or not the node should be included in the route. This factor must be considered to prevent bottlenecks, provide reliable routing, and lengthen the network's lifespan.

2. Need to Mitigate Packet Drops in MANET Due to Constrained Energy

MANETs are wireless networks in which mobile nodes can talk to each other without a stable infrastructure. In MANETs, each node has a limited amount of battery power. Since MANETs lack central coordination and are peer-to-peer networks, it is important to handle energy to keep the network running as long as possible.

Energy management in MANETs is hard because nodes can only store so much energy, batteries are hard to replace, and nodes that have run out of energy can't communicate and must be removed from the network. Inactive energy use happens when the node is not doing anything but waiting for communication requests from other nodes. Energy is also used when the node sleeps [32-34].

To solve the problem of managing energy, many researchers have made routing protocols that not only provide efficient and correct paths between the source and the target but also take energy management into account to make the network last longer. Energy-efficient routing uses the transmission power of nodes to find the route, while reliable routing uses the estimated number of transmissions to find the route. The energy awareness of nodes determines the way with higher energy nodes.

Table-1 summarize the routing protocols designed in MANETs based on the energy consideration. But these protocols don't take into account the chance that intermediate nodes could slow down the network. When the current energy or node hits the threshold amount of energy, it is used to find the path between communicating entities. In this case, it's impossible to guarantee a safe route for heavy traffic, and the route gets crowded, putting the nodes in between bottlenecks. If a node's energy is low and it is still taking a lot of traffic, Because of the size of its buffer and the amount of power it has, it may drop files and lose power right away.

In summary, energy management is important in MANETs because batteries only have so much power and different routing methods have been made to make the network last longer. But these methods don't take into account the fact that intermediate nodes could become bottlenecks, which can cause packet loss and an instant loss of energy. So, when making energy-efficient routing protocols for MANETs, researchers need to consider this problem.

3. Analytical Model for an Intermediate Bottleneck Node

The analytical model takes into account a mobile ad hoc network that is multi-hop and has heterogeneous mobile nodes that are randomly dispersed across a geographical region. When communicating nodes are not within communication range of one another, an intermediary node in this network takes on the role of a router and forwards the packets. Energy awareness and residual/threshold energy level are the three components of the route selection metric [6]. While trying to forward packets from several sources, the intermediate node might sometimes cause a bottleneck. The Poisson point distribution is a good tool to use when you want to estimate the number of different mobile nodes spread out over a large area.

Before initiating communication between the source and the destination, it is necessary to configure an intermediate node to ensure uninterrupted communication. An intermediate node must have sufficient energy and buffer space to forward transmissions. We take into account heterogeneous mobile locations with the following features.

Table 1. Energy based routing in MANETs

Protocol	Objective	Goal
Energy-efficient route	1. Anticipated Energy Intake 2. Routing of Energy Drain Rate 3. Distributed Efficient Energy Routing 4. Lowest Energy Route	Minimize-Energy consumption
Reliable route	1. Load-Aware Route 2. Transmission-Count-Expected Route 3. Retransmission Energy-Conscious Route	Provide-Reliability of Link
Route with greater energy nodes	1. Energy-Aware Local Routing 2. Lifetime prediction route planning 3. Battery-Aware Routing 4. Energy-Aware Integrated Routing 5. Energy-dependent QoS routing 6. energy-aware dynamic routing	Extend-Network Life Time

1. An intermediate node could be a sleeping node or an active node.
2. The intermediate node can hold an ‘L’ number of packets and has an inline buffer and an outline buffer.
3. It begins by storing the data packets that it obtains from the source node in the inline queue, and then it evaluates the data packet and moves it into the outline queue once a decision has been made about it.
4. An intermediate node can process a greater number of data packets, i.e., (n)in the $('T')$ time interval if the amount of energy available is sufficient and if the amount of traffic is kept to a minimum.
5. An intermediate node has a defined capacity to process a certain number of packets, i.e., (α) moving from its inline to its outline within a certain time interval, denoted as τ.Then the average energy drain rate of a node$E_{dr}\ joules/second$with a packet rate of $(\alpha)/_{\tau}$Packets per time interval.
6. It is possible for there to be congestion at an intermediate node if there are more than α” packets that arrive at the node during the time interval ‘τ, and the node will drop the packets if the drain rate gets higher than $E_{dr}\ joules/second$within a τ interval. Further, it causes the node to die and affects the network lifetime.

Assuming the energy decrease at an intermediate node is random, this study computes the packet drop owing to the congestion and exceeding drain rate. The following equation can be used to get the average amount of energy saved in each packet, indicated as ;

$$\vartheta = (energy\ drain\ rate\ of\ the\ node) / (number\ of\ packets)$$

If the mean value of energy reduction per packet processed during a brief period Δof t secondisϑ, then the chance of energy reduction occurring during the processing of a single packet within Δt seconds is ϑΔt. In contrast, the probability that a single packet procedure will not reduce energy within t seconds is 1 − ϑΔt. These probabilities can be utilized to analyze the behavior of a system, including packet processing and energy savings. For instance, they can be used to predict the projected overall energy reduction owing to packet processing within a certain time frame or to calculate the likelihood of congestion or node failure caused by an excessive energy drain.

The Poisson distribution approach can be used to calculate the likelihood that a node will experience an exact δ amount loss in energy owing to ‘n’ arrivals in time ‘t’. The number of packets that cause energy reduction follows a Poisson distribution with mean $\lambda = n * \vartheta\Delta t$

Thus, the probability of exactly $'\delta'$ amount of energy reduction occurring due to ‘n’ arrivals in a time ‘t’ is computed by:

$$P(\delta) = (e^{\wedge}(-\lambda) * \lambda^{\wedge}\delta) / \delta!$$

$$where\ \lambda = n * \vartheta\Delta t.$$

The probability of no energy reduction occurring in a larger time interval (t) is given by the exponential distribution $P(0) = P(\omega > t) = e^{\wedge}(-\vartheta\Delta t)$.

The probability distribution function calculates the likelihood that a given number of packets will result in a particular level of energy reduction in an intermediate node during a given time interval. The probability density function is then utilized to determine the energy reduction rate per unit of time. These computations are valuable for analyzing system behavior, such as packet processing and energy savings. They can be used to anticipate the probability of congestion or node failure due to excessive energy drain. The probability distribution function A(t) and probability density function f(t) can be written as:

$$A(t) = 1 - e^{\wedge}(-\delta t), where\ t > 0$$

$$f(t) = (\partial A(t))/\partial t = \delta e^{\wedge}(-\delta t)$$

Further, we computed the probability of $'n'$ packets present in the node buffer by the following equation,

$$P(n) = (\mu/\alpha)^{\wedge}n * (1 + \mu/\alpha)^{\wedge}(-1) * (1/((1 - \mu/\alpha) * ln(1 + \mu/\alpha)))$$

Where, μ is packet arrival, and α is packet departure from the node’s buffer.

Further, we computed the probability of the packet spending more than t seconds in the node’s buffer by the following equation.

$$P(waiting\ time > t) = e^{\wedge}(-(\mu - \alpha)t) * (\mu/\alpha)$$

The above computation estimates packet loss in a mobile ad hoc network. The Poisson point distribution method is utilized to determine the energy reduction per transmission, i.e., the mean value of energy reduction per packet, denoted by ϑ. The mean value of energy reduction per packet can be calculated by dividing the energy depletion rate of a node by the number of packets. This value is then employed to calculate the probability of energy reduction occurring during the processing of a single packet within a brief time interval Δt, as well as the probability that a single packet procedure will not reduce energy within t seconds.

In addition, the probability distribution function is used to determine the probability that a given number of packets will result in a specific level of energy reduction in an intermediate node during a given time interval. This computation is necessary for estimating packet loss because it determines the likelihood of packet congestion, which leads to packet loss. The probability density function is then used to determine the energy reduction rate per unit of time, which is essential for analyzing the system’s behavior and predicting the likelihood of congestion or node failure due to excessive energy depletion. Table 2 shows the analytical model notation and their corresponding values.

Table 2. Numerous aspects of a mobile ad hoc network, such as packet processing, energy savings, and the likelihood of congestion or node failure due to excessive energy depletion, can be analyzed using equations and probabilities.

Description	Equation or Probability
The mean value of energy reduction per packet	ϑ = (energy drain rate of the node) / (number of packets)
Probability of energy reduction due to a single packet	$\vartheta\Delta t$
Probability of no energy reduction in time t	$P(0) = e^{(-\vartheta\Delta t)}$
Probability of δ amount of energy reduction in time t	$P(\delta) = (e^{(-\lambda)} * \lambda^{\delta}) / \delta!$, where $\lambda = n * \vartheta\Delta t$
Probability of n packets in the node buffer	$P(n) = (\mu/\alpha)^n * (1 + \mu/\alpha)^{(-1)} * (1/((1- \mu/\alpha)*\ln(1+ \mu/\alpha)))$
Probability of packet waiting time > t	$P(\text{waiting time} > t) = e^{(-(\mu-\alpha)t)} * (\mu/\alpha)$
Probability distribution function A(t)	$A(t) = 1 - e^{(-\delta t)}$, where $t > 0$
Probability density function f(t)	$f(t) = (\partial A(t))/\partial t = \delta e^{(-\delta t)}$

Additionally, the probability of ‘n’ packets being present in the node buffer and the probability of a packet occupying more than ‘t’ seconds in the node buffer is calculated. These values are used to calculate the estimated packet loss because they provide information about the buffer capacity and traffic flow through the node. Suppose the number of packets arriving at the node exceeds its capacity, and the probability of a packet lingering in the buffer for longer than a specified time is high. In that case, the node will drop the packets. By analyzing these probabilities, it is possible to estimate the packet loss and control the traffic toward the input buffer to prevent packet loss.

Consequently, by utilizing the analytical model and probability distributions, the packet loss estimation can be accurately calculated, and traffic can be controlled effectively to prevent packet loss and enhance network performance.

3.1. Routing based on the Analytical Model

To establish and maintain connectivity, each node in the network periodically transmits a “hello” message to its neighbours. When a node needs to send a transmission to a destination node, it first uses the analytical model to determine the status of all neighbouring nodes. If a node is identified as a bottleneck by the analytical model, it is removed from the list of potential routing candidates. The remaining nodes are ranked according to their estimated distance and dependability using a weighted metric that takes signal strength, and hop count into consideration. The source node selects and transmits the highest-ranked candidate node as the packet’s next step. When the packet reaches the next hop node, the process of determining the best candidate node for packet forwarding is repeated. This procedure is repeated until the capsule reaches its final destination. If a node loses connectivity with its neighbours, it transmits a new welcome message to reestablish connectivity. If a node becomes a bottleneck due to excessive traffic or other factors, it alerts its neighbours, who then update their routing tables accordingly. The routing algorithm is an extention of the existing reactive AODV algorithm; the extention of the proposed algorithm is shown in algorithm-1.

Algorithm1: Routing computation based on the bottleneck node prevention

```
function MANET_Routing(node, destination):
   neighbours = get_neighbours(node)
remove_bottlenecks(neighbours)
   if destination in neighbours:
transmit_packet(node, destination)
      return
   candidates = rank_neighbours(neighbours)
next_hop = select_best_candidate(candidates)
transmit_packet(node, next_hop)
   while not packet_received_by_destination()
      neighbours = get_neighbours(node)
remove_bottlenecks(neighbours)
      candidates = rank_neighbours(neighbours)
next_hop = select_best_candidate(candidates)
transmit_packet(node, next_hop)
   return
```

4. Performance Analysis

We investigate a MANET environment in which 200 mobile nodes are dispersed across a 1000 by 1000 square unit area. Each node has an individualized radio range. The buffer capacity of each mobile node is 10 packets, and the packet lifespan is 10 packet durations. The node packet processing time is between 0.005 to 0.0045 seconds, and the source creates packets with a packet interval time of 5 milliseconds. Using probability distribution, we determined several performance metrics for this network, as follows:

We determined the time messages must wait in the input buffer of an intermediate node before being forwarded. This waiting time depends on the node’s packet processing speed and incoming traffic. We calculated this waiting time for packet processing times of 0.005 and 0.0045 seconds and the probability of average waiting time for various incoming traffic levels. This metric is utilized to ascertain the time-to-live (TTL) value of a packet. If the waiting time exceeds the TTL of the message, it is removed from the queue, shown in Figures 1, 2, and 3.

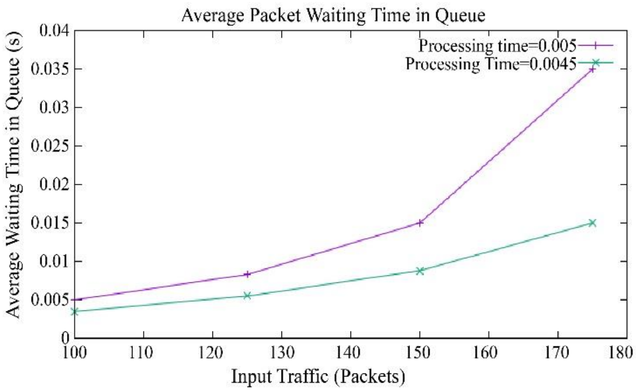

Fig. 1 Packet average waiting delay inside the buffer of an intermediate-node

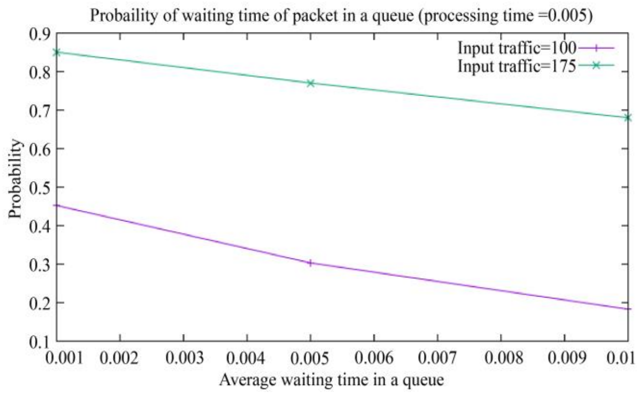

Fig. 2 Probability of packetaverage waiting delay inside the buffer of an intermediate node (Processing time = 0.005 seconds)

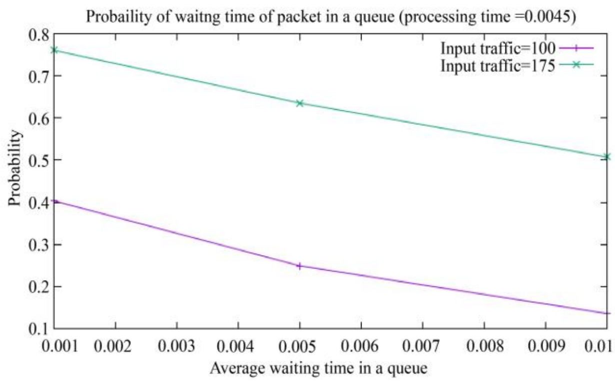

Fig. 3 Probability of packetaverage waiting delay inside the buffer of an intermediate node (Processing time = 0.0045 seconds)

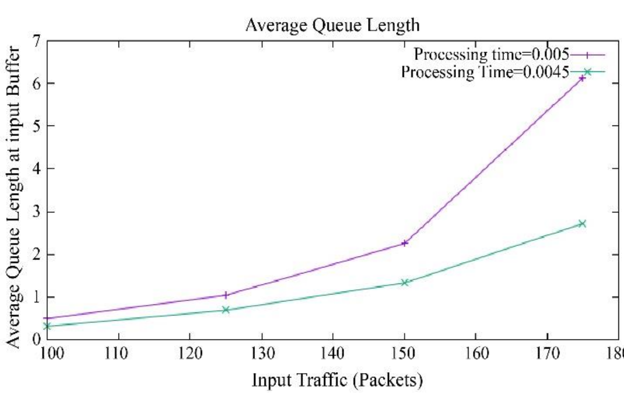

Fig. 4 Average queue length at an intermediate node's input buffer

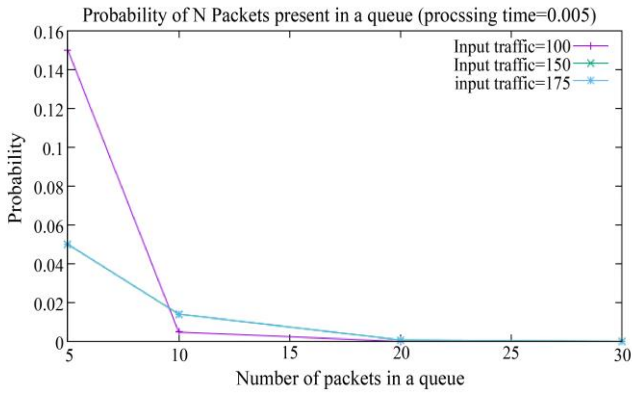

Fig. 5 Probability of N packets inside the buffer of an intermediate node (Processing time = 0.005 seconds)

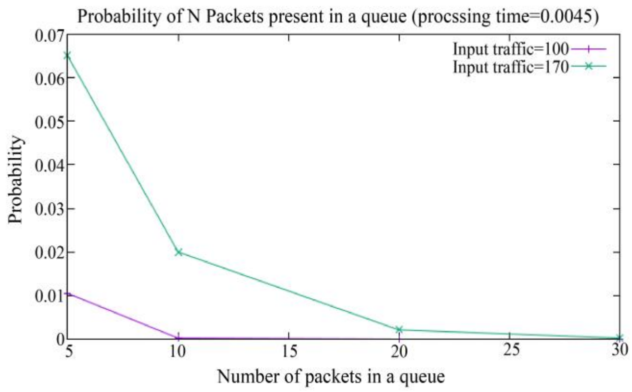

Fig. 6 Probability of N packets inside the buffer of an intermediate node (Processing time = 0.045 seconds)

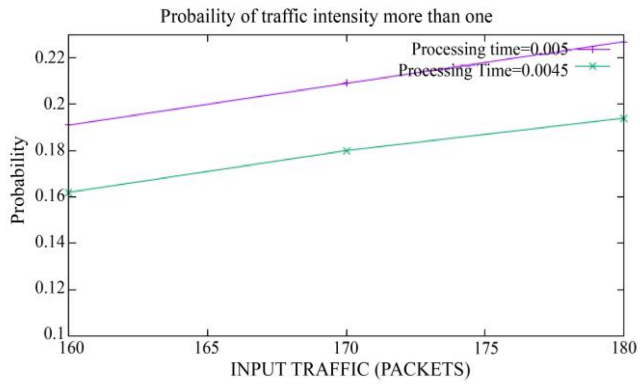

Fig. 7 Probability of packetaverage waiting delay inside the buffer of an intermediate node relative to traffic volume

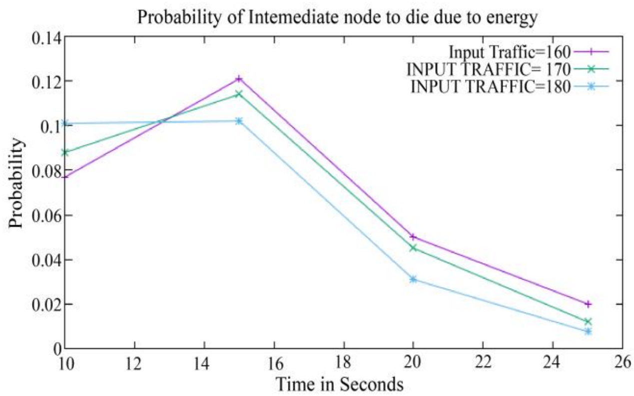

Fig. 8 The probability of node demise increases as a result of energy

We calculated the average queue length of messages in the input buffer of an intermediate node before transmission. This queue length depends on the node's packet processing speed and incoming traffic. We calculated this queue length for 0.005 and 0.0045 seconds of packet processing time and the probability of packets being present in the input buffer for varying incoming traffic levels. This metric is used to determine the capacity of the node's input buffer. If the queue length exceeds the buffer capacity, input buffer packets are dropped, shown in Figures 4, 5, and 6. Given the arbitrary nature of the traffic intensity at an intermediate node, we calculated the packet loss probability from an intermediate node using a Poisson random process, as shown in Figure 7.

Further, we calculated the probability of a node losing exactly 10 J of energy due to various packet arrivals at a time, 't'. Under these conditions, the probability of energy loss due to the processing of one packet in 0.005 seconds is 0.0045 J. This metric provides information regarding the energy consumption of network elements, shown in Figure 8. Our analysis demonstrates that increasing packet processing time improves performance by decreasing waiting time and queue size. As incoming traffic to an intermediate node increases, so does the network lifetime. Nodes with low processing times and high incoming traffic rates are more likely to lose packets.

The results of the proposed routing mechanism for self-forming and adaptable MANETs with peer-to-peer and heterogeneous nodes are promising. The proposed mechanism aims to minimize packet loss due to buffer overflow and energy restrictions by selecting intermediary nodes that are energy-efficient and uncongested. The effectiveness of the proposed mechanism is evaluated using simulation experiments.

Figure-9 shows the relationship between buffer space and packet delivery ratio. The results indicate that the packet delivery ratio increases as the buffer space increases. This is because, with larger buffer space, intermediate nodes are less likely to drop packets due to buffer overflow, resulting in fewer packet losses.

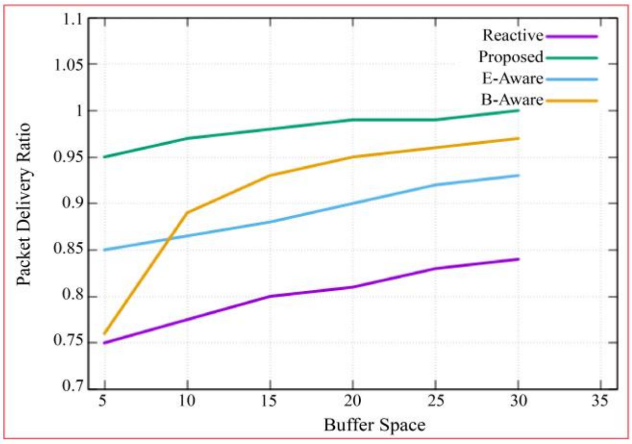

Fig. 9 Performance comparison of proposed work existing energy aware, buffer aware, and reactive routing protocols in terms of Packet delivery ratio vs Buffer space

5. Conclusion

This research provides a mathematical methodology to evaluate intermediate bottleneck node performance in Mobile Ad Hoc Networks (MANETs) to address battery life. The study focuses on the latter and introduces infrastructure-based and infrastructure-less wireless network communication models. MANETs are dynamic, transient, self-organized networks of mobile nodes that connect via intermediary nodes. Since mobile nodes have inadequate battery power, the paper emphasizes MANET energy efficiency. Routing protocols should account for packet energy use and enable reliable routing over networks while enhancing the Quality of Service. The research presents a toxic random process-based analytical model to evaluate an intermediate bottleneck node's performance. MANETs with heterogeneous mobile nodes randomly disseminated across a region are modeled. The intermediate node must have enough energy and buffer capacity to forward packets, and the model calculates the normal input buffer queue length and wait time. The model controls intermediate node traffic and determines if it should be included in the route. This element must be considered to avoid bottlenecks, provide reliable routing, and extend network lifespan.

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