Comparative Analysis Between Four Models of IoT Gateway Selection

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Declaration

It is hereby declared that

1. The thesis submitted is my/our own original work while completing degree at Brac University.

2. The thesis does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.

3. The thesis does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.

4. We have acknowledged all main sources of help.

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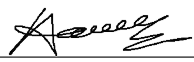

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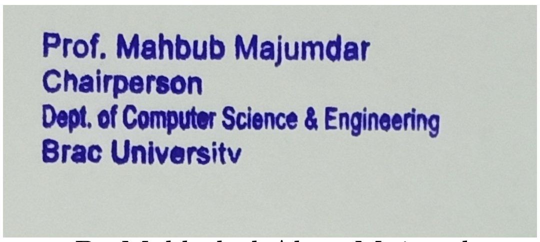

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Abstract

The “Internet of things” (IoT) is a leading sector of technology where usual analog devices can be turned into smart devices with embedded systems and sensors. These devices can communicate with each other without requiring any human to human or human to computer interaction and automate various aspects of human lives. With the growing application of IoT some of the crucial challenges faced in this sector are maximizing throughput, minimizing energy consumption of the gateways and balancing loads among the gateways efficiently. Not to mention providing high throughput and low energy consumption at the same time is a contradictory concept and the selection models have to reach the most optimum trade-off point to offer better performance. There are various models that have been proposed for IoT gateway selection, each of which comes with various pros and cons. Hence we decided to conduct a comparative analysis between a few of the most innovative and promising Gateway Selection models to find out which of these models are relatively more effective to tackle the above-mentioned challenges in IoT. For our research, Game Theory Gateway Selection (GTGWS), Taxi-Sharing, Floyd-Warshall & Minimax (FWM) Algorithm and Evolved Reliability and Traffic-aware Gateway Selection (ERTGS) model were studied. To ensure the credibility of this analysis the models are tested under two distinguished network conditions - different ‘demand’ of the end devices & different ‘number’ of end devices connected to the gateway. Under the given scenarios, various data were obtained. For instance, given a least congested network, bandwidth usage by these four models were: ERTGS utilizes 30.464%, Taxi-Sharing utilizes 15.25%, FWM utilizes 12.5% and GTGWS uses 21.68% of the total bandwidth. Various results like these were obtained for other evaluation criteria such as load difference and energy consumption; after careful analysis it was found that none of the four models offers optimal solutions to all of the challenges; and that different models are better suited for different network priorities which are discussed in details in this paper.

Keywords: IoT; Gateway Selection; Throughput; Energy-Consumption; Load-Balancing; Efficiency; GTGWS; Taxi-Sharing; FWM; ERTGS

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Nomenclature

The next list describes several symbols & abbreviation that will be later used within the body of the document

BDT Bangladeshi Taka

ERTGS Evolved Reliability and Traffic-aware gateway selection

FWM Floyd-Warshall & Minimax

GTGWS Game Theory Gateway Selection

IoT Internet Of Things

IP Internet Protocol

J Joule

KB kilobyte

MBps Megabytes per second

ms millisecond

NP Non-deterministic Polynomial Time

RM Malaysian Ringgit

W Watt

WBN Wireless Body Area Network

Chapter 1

Introduction

1.1 Background

Internet of Things (IoT) has been defined in many different ways by [25][36][46], we have combined their ideologies to state that IoT is a system of interconnected digital objects, machines, animals or humans that connect and share data with each other over the Internet. It consists of devices that can be as small as a chip implanted on a human's heart to something as big as a sensor attached in a vehicle to help it navigate through roads. One of the greatest advantages of IoT is that it allows data transfer without needing any human to human or human to computer interaction. All it requires is an Internet Protocol (IP) address which is assigned to each of this "thing" on the Internet that will allow them to communicate with each other across the Internet [20][21]. With the growing demand for the IoT, the number of connected devices on the Internet is accelerating exponentially; this indicates that there is a large demand for IoT gateways [41]. Therefore, it is crucial that there are efficient models for selecting IoT gateways for data transmission.

There have been many existing and proposed gateway selection scheme in IoT. Such as, Direct Transfer, Lowest-Cost, Shortest-Queue-First, Deadline-Cost, Deadline-Shortest-Queue-First, Taxi Sharing, Game Theory Gateway Selection (GTGWS), Genetic Algorithm, Floyd-Warshall & Minimax model (FWM), Evolved Reliability and Traffic-aware gateway selection (ERTGS) just to name a few. To make the gateway selection more efficient, these selection models focus on different aspects of the network such as improving the load-balance on the gateways, lowering energy consumption and cost, enhancing link quality and speed, lowering network latency, increasing throughput etc. It is crucial to select the IoT gateways in such a way that it does not create any deadlocks, loss of packets or congestion in the network. Hence efficient selection of the gateways must be the utmost priority while communicating with various devices over the Internet. For this study Taxi-Sharing model, FWM model, ERTGS and lastly, GTGWS model will be given priority. The reasons for choosing these models are:

- GTGWS: This model selects the gateway based on the demand of the end devices and load balance on the gateway. Moreover, it uses the concept of Nash Equilibrium, which has a potential of increasing the efficiency of data transfer [41].

- FWM: This model uses both Floyd-Warshall and Minimax algorithm to find a gateway approximately located at the center of the network service area. This would allow each end devices to have the shortest distance from the gateway [43].

- Taxi-Sharing: This model uses the concept of Delay-Tolerant Data and compresses the data during transmission, unlike the other three models. This might increase its potential to be one of the most efficient models for gateway selection [40].

- ERTGS: This model uses the concept of reliability by carrying out various combinations of algorithm to choose the gateway. It also uses the concept of Genetic Algorithm which has been proved to be very promising concept in the field of computer science. Hence we chose this model as one of the models for our comparative studies [31].

1.2 Aims and Objectives

GTGWS, Taxi-Sharing, FWM and ERTGS models propose ways to increase efficiency for IoT gateway selection. The aim of this research is to conduct a comparative analysis among these four models to see how they perform, in terms of load balancing, energy consumption and throughput during data transmission; and which of these four models show promising results over the other. The research objective is to evaluate their performances under various scenarios. For instance:

- Under non-uniform and random distribution of end devices.

- Under different demand (in MBps) of end devices and analyze what happens when the demand increases.

- Under different number of end devices and analyze what happens when the number of end device increases.

1.3 Scope and Limitation

This research paper will provide a common platform to the future researchers and IoT experts where they will find all the necessary knowledge required to compare between the four gateway selection models - GTGWS, Taxi-Sharing, FWM and ERTGS. The results and analysis obtained from this study, will help them have a much better insight about these models while developing various IoT applications. However, this research comes with various limitations as well. They are as follows:

- Complexity increases exponentially with the increase in node number.

- There are few assumptions made for all the four models, they are as follows:

  1. All the gateways have the same bandwidth of 50 MBps.
  2. Packet size is considered to be 50 KB for all simulations.
  3. Network Latency is assumed to be 65 ms for all gate-gate connection.

4. Network Latency is assumed to be 60 ms for all gate-end device connection.

The biggest challenge of this research was to build and simulate the network topology. Network characteristics such as: number of end devices and gateways, data transmission rate, bandwidth and packet size were identical for all the models. This was to maintain consistency in data but it also caused limitations. Moreover, for our research we initially wanted to simulate the models for a large number of devices but ERTGS model shows Non-deterministic Polynomial Time, NP-hard problem due to which we were only able to run the simulation for a maximum of 100 devices. Hence, given that our tests and simulations have been on a theoretical basis and under various limitations such as maintaining identical network characteristic, the results we obtained may not fully represent the outcome that will be derived from a real life scenario.

1.4 Thesis Outline

The structure of rest of the paper is as follows. Literature reviews and related works are described in Chapter 2. The explanation of four models GTGWS [41], Taxi-Sharing [40], FWM Algorithm [43] and ERTGS [31] have been described in different subsections of this chapter. In Chapter 3, methodology of this research has been discussed which includes the procedure that were carried out in implementing the four models and how different scenarios were created to test their performances. Chapter 4 describes the implementation and result analysis part where different procedures have been discussed for implementation along with various testing results. Chapter 5 concludes the paper which summarizes the whole research and talks about our future work.

Chapter 2

Literature Review and Related Work

As defined by [26],“A gateway is a hardware device that acts as a ‘gate’ between two networks. It may be a router, firewall, server, or other device that enables traffic to flow in and out of the network. While a gateway protects the nodes within network, it also a node itself. The gateway node is considered to be on the “edge” of the network as all data must flow through it before coming in or going out of the network. It may also translate data received from outside networks into a format or protocol recognized by devices within the internal network”.

Thus it is very clear that gateway plays a crucial role in all types of networking activity. In IoT, gateways act as a single point of access that helps to explore a specific network area. IoT is a ‘sensing’ equipment and it uses various sensors and data to connect anything to the internet. The data from these sensors cannot be sent directly to the data center, it would otherwise be very ineffective in terms of performance and network utilization. IoT gateways pre-process all the data from the IoT sensors before they are sent to the data center. Such pre-processing includes message filtering and aggregation. These gateways also play an important role in connecting these sensors with external networks by using WiFi, GSM, or some other type of connectivity. The most helpful feature of IoT gateway is that it gathers all the necessary metrics from the sensors and act as a common platform to access those data. [45][27]

The main obstacle in developing models for IoT gateway selection is that there is no standard i.e. each node communicates with the gateway using different protocols which may not be compatible to others. As a result it becomes very difficult to develop a general purpose gateway for IoT. This is why there are many existing and proposed IoT gateway selection schemes for various applications. However all of them share a common interest and that is to increase efficiency of data transfer while maintaining low cost and energy consumption [35] There have been many previous works where selected IoT gateway models were studied and compared to each other based on various assessment criteria. For instance, in [19]the author carries out performance comparison of different Gateway Load Balancing methods such as Distributed, Traffic Distribution, Cluster based and Centralized method for Load Balancing. In this paper the author compared these models based on various evaluation criteria such as cost effectiveness, threshold value and channel assignment. Our paper focus on similar comparative studies where four different models- Taxi-Sharing, GTGWS, FWM and ERTGS are compared under various evaluation criteria such as: energy consumption, throughput and load balancing. This chapter focuses on these four models and the related work to these models. The working principles of these models are also explained in the subsections.

2.1 Taxi-Sharing: A Wireless IoT-Gateway Selection Scheme

2.1.1 Background

The Internet of things is being implemented in countless sectors nowadays due to rapid growth and improvement of technology and optimal gateway selection is a crucial factor in IoT. Within gateway selection, there are other problems to deal with as well such as minimizing cost and traffic, load balancing, saving time to provide faster service etc. The taxi-sharing model aims to minimize cost of data transmission and balance the load of data traffic. With the increasing number of IoT devices, the data transmission cost is also increasing. Companies in this sector have to spend around 5 million dollar a year to manage 1 million IoT devices where 20% of this cost is spent on transmission expenses[30]. The model takes into account transmission cost and latency of other gateways of the path to select the best gateway while it also compresses data by waiting until the eleventh hour of deadline. As a result, a lesser amount of data is transmitted over the radio frequency which contributes to minimize data transmission cost.

A lot of significant work has been done in this field by many researchers. In [34] the proposed Adroit algorithm mainly works with V-mesh network and attempts to resolve packet loss, delay and deployment cost. The main four stages of the algorithm are gateway broadcast, selecting on-hand gateway, base station broadcast and base station selection. A comparative study in [22] showed a comparison between four algorithms in terms of performance in different sizes of network. The algorithms were Monte Carlo-based Gateway selection (MCS), Centrality-based gateway selection (CBS), Frequent trajectory based gateway selection (FT) and random selection. The result showed that FT works better in smaller network size and CBS is better for bigger network size. MCS is a good choice for high complexity and finding optimal gateway. Another study in [38] compared deadline-cost (DC) and Deadline-queue-first (DSQF) in terms of efficiency in cost reduction by using shortest-queue-first as the reference point. Deadline-cost (DC) performed better according to the study. While the above-mentioned algorithms either take into account performance or cost, the routing protocol proposed in [28] named multi-path load balancing technique focuses on load balancing in Mobile Ad-hoc network. Firstly, it detects congestion and then it selects the gateway node using link cost and path cost.

From the discussion above it is clear that the discussed algorithms do not focus on both minimizing cost and balancing the traffic load while selecting an optimal gateway and this characteristic distinguishes the Taxi-sharing model proposed in [40] from others. Data deadline and cost has not been the research priority for many researchers and this is why the Taxi-sharing algorithm has been proposed to contribute in this area. Since data compression is a significant part of implementing taxi-sharing, to select a data compression algorithm, the comparative study of data compression algorithm in [17] has helped to a great extent. In this paper Deflate, LZ77, LZW and Huffman algorithms have been compared based on their performance and Deflate algorithm has been chosen for compressing data in the implementation of Taxi-sharing algorithm.

2.1.2 Working principle of Taxi-sharing scheme

The scheme in [40] is inspired by the taxi-pooling method used in urban areas to reach destinations by sharing the vehicle with multiple people to reduce transportation cost. After arriving at the station, the passenger can communicate with other nearby passengers to check if they also want to reach the same destination within a specified time. If the passenger can find other people to share the vehicle with, they can split the bill afterwards and this reduces their individual bill. In addition to that, there are fewer vehicles when multiple people share one taxi instead of getting one taxi for each passenger which reduces traffic congestion.

In a similar way, internet gateways distribute the data among themselves to send the overall data to cloud with least possible cost while not violating the data deadline. Since this model works with delay tolerant data, each sensor data packet has a specific deadline within which it has to reach the destination. The gateways maintain queues to store the data packets coming from sensors and other gateways. Since different data packets will have different deadlines; the gateways store the data packets with the same deadlines together and compress them together before sending them out to the cloud. However sometimes data packets may arrive which cannot find a local queue with its deadline to join. Instead of starting a new queue right away the neighboring gateways and their queues can be evaluated within the time allocated in the deadline to minimize cost and the Taxi-sharing algorithm utilizes this technique. Here the data packets can be considered as the passengers and the cloud is the destination of these passengers. The queues maintained in the gateways can be compared to taxis.

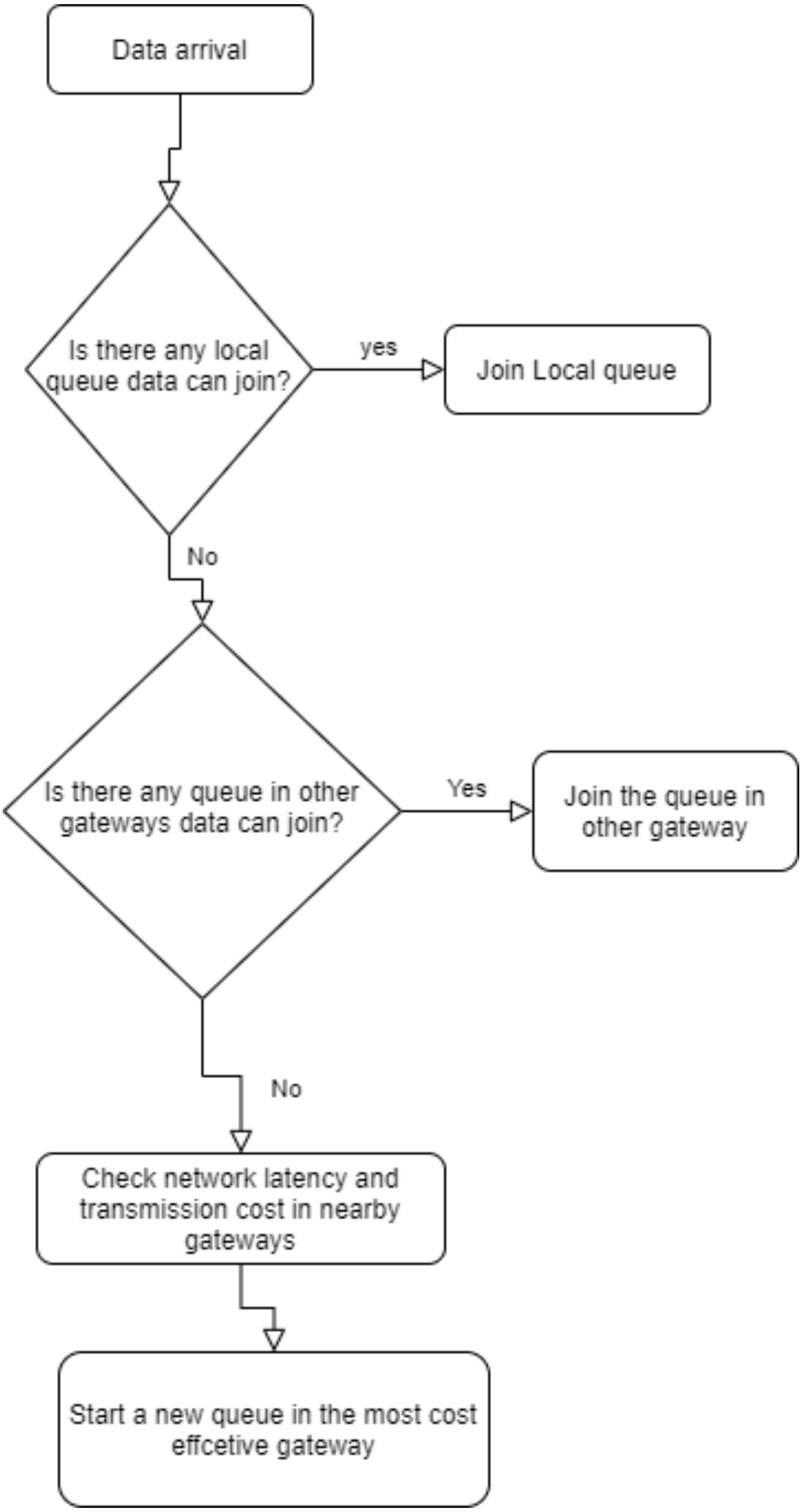

Figure 2.1: The Taxi-Sharing Working Scheme

The parameters of this scheme are given in the below table.

Term	Definition
V	Set of all Gateways
G	Selected Gateway
i	A selected node in V
m	message
MQ	Message Queue
$d(m)$	Deadline of message m
$K(i)$	Set of deadlines of existings queues in ith node
QF	A boolean flag denoting a queue is found for a specific deadline
j	A selected node in $N(i)$
$N(i)$	Set of neighbours of ith node
h	Hello packet
$JQ(hr)$	Join queue flag of reply packet hr
hr	Hello reply packet
$C(n)$	Cost of data transmission in nth gateway
n	A selected node in $N(i)$
$time$	Delay Tolerant Time
LTi, j	threshold value
$D(h)$	Deadline mentioned in hello packet
$S(h)$	Sender of hello packet
$R(h)$	Receiver of hello packet

Table 2.1: Terms used in Taxi-sharing algorithms

The main principle of this algorithm is to group data with a similar deadline as much as possible. In Algorithm 1, after receiving a data packet from the connected sensors, the gateway will first check if there is any local queue that the packet can join. If there is not any queue available then the gateway will send hello packets to its neighbors with the information of the deadline of the recently received packets from sensors. The neighbors who are inactive will be ignored since they would not reply to the hello packet. Gateways who are active, will reply to this hello message with their information about available queue, data transmission cost and latency.

Then in the received message, a queue is found with a similar deadline, the packet will be sent to that Gateway where the packet can join a queue. If there is no queue available even in the neighbour gateways, the cost and latency is evaluated to start a new queue in the most cost-effective gateway. When data joins or starts a new queue in another Gateway only considering the deadline of the data would not be enough because the data would have to travel some time to reach that gateway.The actual time spent to reach cloud would be the total of time to reach the Gateway and then the time while the data would be waiting in the queue of that gateway. This is why, while evaluating the neighbouring gateways, the time considered is the difference between data deadline and the latency of the path to that gateway so that the data can reach the cloud within its deadline. [40].

Algorithm 1 Taxi-sharing

Input V
Output G

for each $i \in V$ **do**
  for each $m \in MQ$ **do**
    if $d(m) \in K(i)$ **then**
      $G \leftarrow i$
      $QF \leftarrow true$
    else
      for each $j \in N(i)$ **do**
        Send h to j
        Algorithm 2
        if $JQ(hr) = true$ **then**
          $G \leftarrow j$
          $QF \leftarrow true$
    if $QF = false$ **then**
      Sort $n\, in\, N(i)\, according\ to\ C(n)$
      for each $n \in N(i)$ **do**
        $time = d(m) - LT_{i,n}$
        if $LT_{i,n} < time$ **then**
          $G \leftarrow n$
          $QF \leftarrow true$
          $break$

Algorithm 2 shows how a gateway replies to a hello packet.When a gateway receives a hello packet, it checks if there is any queue available within required time. The gateway considers the required time in above mentioned away. It gets the deadline information and sender information from the hello packet. If it can find a queue within a defined constraint it assigns the join queue flag in reply packet to be true and otherwise it is false. To complete the overall process the data waits as long as possible without violating the deadline to find the most cost-efficient way. Due to this gateway selection scheme the data transmission cost reduces significantly. Large sum of data is compressed together which reduces overall data to be transmitted in the communication channel. Along with decreasing data transmission cost, it also decreases traffic congestion which results in better load balancing among gateways. However, this compressing in the gateway end and decompressing in the receiver requires extra power consumption and time.

Algorithm 2 Replying to Hello packets

Input H
Output JQ

$s \leftarrow S(h)$
$r \leftarrow R(h)$
$time = D(h) - LT_{s,r}$
if $time \in K(s)$ **then**
  $JQ(hr) \leftarrow true$
  Send hr to s

2.2 Gateway Selection Based on Game Theory in Internet of Things

2.2.1 Background

Game Theory - also known as 'Interactive Decision Theory' - the concept was introduced by Neumann and Morgenstern's in 1944 in a book called Theory of Games and Economic Behavior [2]. Game theory is the theory of "strategic thinking" which is used in many areas such as economics, engineering, computer science, just to name a few [18].

It is the mathematical theory that focuses on decision making in certain scenarios where each player's decision can influence the outcomes of other players. In such settings, each player must consider how each other player will act in order to make an optimal choice. Game theory is generally divided into two branches, which are non-cooperative and cooperative game theory [14]. In [6] Lim further clarified that whether a game is cooperative and non-cooperative would depend on whether the players can communicate with one another. Non-cooperative game theory focuses on strategic choices where each player chooses its strategy independently for improving its own utility. To solve non-cooperative games a concept known as Nash Equilibrium is used.

According to [15], Nash equilibrium was introduced by John Nash in 1950 and has emerged as one of the fundamental concepts of game theory [1]. [7] defines Nash Equilibrium as-"A solution concept of a game involving two or more players, in which each player is assumed to know the equilibrium strategies of the other players, and no player has anything to gain by changing only his own strategy. "

Tzung-Shi Chen and Bo-Han Wu used the concept of non-cooperative games and proposed a Game Theory Algorithm for efficient gateway selection in IoT [41]. There are various gateway selection criteria that the Authors of [41] mentioned that relates to his proposed model; such as [29] and [31]. In [29] an M2M Gateway Selection Scheme was proposed where the selection is based on the number of gateways connected to the devices & the percentage of gateway residual bandwidth. In [31] the authors worked with Gateway Selection Game in Cyber Physical Systems where they suggested a model where the sensors compete for the bandwidth with various devices using game theory. Moreover,the competition for resources exists between the devices in the gateway.By considering these models the Tzung-Shi Chen and Bo-Han Wu proposed GTGWS model where the IoT gateway selection is based on a pre-defined utility function [41].

2.2.2 Working principle of Game Theory Gateway Selection Model

This model focuses on the non-cooperative dynamic game where the end devices are the game "players". The gateways within the network are the devices that select the strategy of the game. There are few assumptions made in this model. They are as follows:[41]

1. Each gateway has the same bandwidth (50 Mbps)
2. New Players (end devices) cannot join the game until the end of the game.
3. Each participant only pursues the maximum utility strategy.

The model uses a pre-defined Utility function and based on this function Utility Strategy of each gateway is found which is used during the gateway selection process. To derive the utility function, this model takes into account various important factors [41]. They are as follows:

1. Recieved Signal Strength (Rssi): *Rssi* is calculated using predefined maximum signal strength P_0 (estimated 1 meter from the gateway), *pl* (path loss value usually set at a value of 2 to 7) and distance *dist* (distance between the end device e and the gateway g).

$$Rssi_{ei}^{gj} = P_0 - 10 \times pl \times \log_{10}(dist_{ei}^{gj}) \tag{2.1}$$

2. Received Signal Power: In the equation below, P_{ei} is the Received Signal Power & P_g is the gateway power set to 10 mW.Using equation (2.1) Rssi value is calculated.

$$P_{e_i} = \frac{P_g}{10^{\frac{\left|Rssi_{e_i}^{gj}\right|}{10}}} \tag{2.2}$$

3. Received Noise Power: In equation (2.3) k are the end devices connected to the gateways. e_i is the current player taking part in the game of selection.

$$P_{noise} = \sum k \left(\frac{P_{e_i}}{dist_{e_i}^{e_k}} \right) \tag{2.3}$$

4. Signal to Noise Ratio(SNR): SNR is calculated using equation (2.2) & (2.3). SNR is used to calculate Channel Capacity.

$$SNR = \frac{P_{e_i}}{P_{noise}} \tag{2.4}$$

5. Channel Capacity: The channel capacity is considered between the end device e and the gateway g. W is the bandwidth of the channel. SNR is obtained from the results in equation (2.4).

$$C_{ei}^{gj} = W \log_2(1 + SNR) \tag{2.5}$$

After considering the above factors Utility U_i is calculated using the equation (2.6) where B is the bandwidth of the gateway (50 MBps), m is the number of end devices connected to the gateway & K_i is the ratio of demand of the end devices and channel capacity.. In equation (2.7) K_i is calculated, where D_i is the demand of end device and $C_{e_i}^{g_j}$ is the channel capacity between the end device and gateway which is calculated in equation (2.5).

$$U_i = \frac{B}{m} - K_i \tag{2.6}$$

$$K_i = \frac{D_i}{C_{e_i}^{g_j}} \tag{2.7}$$

The parameters and the algorithms used to simulate the model are as follows:

Term	**Definition**
P_0	Maximum signal intensity
pl	Path loss value
P_g	Gateway power
W	Channel bandwidth
B	Gateway bandwidth
e	Number of end devices
g	Number of gateways
m	Number of end device connected to the gateway
k	Number of end devices
dist	Distance matrix
Rssi	Received signal strength
P	Receiver signal power
P_{noise}	Receiving noise power
SNR	Signal to noise ratio
U	Utility value of the strategy
C	Channel capacity
α	threshold value
K	matrix
S'	Strategy array

Table 2.2: Terms used in GTGWS algorithms

Algorithm 3 *CalculatingChannelCapacity*

for $ei = 0, 1, \ldots$e **do**
  for $gj = 0, 1, \ldots$g **do**
    $Rssi_{ei}^{gj} = P_0$ - 10 x pl x $log_10(dist_{ei}^{gj})$
for $ei = 0, 1, \ldots$ei **do**
  for $gj = 0, 1, \ldots$gj **do**
    $P_{ei} = \frac{P_g}{10^{\frac{Rssi_{ei}^{gj}}{10}}}$

for $ei = 0, 1, \ldots$e **do**
  for $ek = 0, 1, \ldots$e **do**
    $P_{noise} = \sum_k \frac{P_{ei}}{dist_{ei}^{ek}}$
for $ei = 0, 1, \ldots$e **do**
  $SNR = \frac{P_{ei}}{P_{noise}}$
for $ei = 0, 1, \ldots$e **do**
  for $gj = 0, 1, \ldots$g **do**
    C_{ei}^{gj} = W log_2(1 + SNR)

Algorithm 4 *KCalculation*

for $i = 0, 1, \ldots$e **do**
  if $D_i - C_i^{S'_i} \leq 0$ **then**
    K[i] = 0;
  else$0 < D_i - C_i^{S'_i} \leq \alpha$
    $K[i] = \frac{D[i]}{C_i^{S'_i}}$

Algorithm 5 *UtilityCalculation*

for $i = 0, 1, \ldots$N **do**
  $U_i(S'_i, S'_{-i}) = \frac{B}{m} - K_i$

The end devices consider their own criteria to select the gateway. The behavior of the end devices is basically a dynamic game which means each end devices dynamically chooses the gateway in an orderly manner. The last mentioned selected device will know the previous node's selection strategy and influence the it's utility. The strategy of the game is to maximize the utility function by using the concept of Nash Equilibrium.

Algorithm 6 *CalculatingNashEquilibrium*

```
for i = 0, 1, ...N do
    U_i(S'_i, S'_{-i}) = B/m - K_i

for i = 0, 1, ...N do
    if U_i(S'_i, S*_{-i}) ≤ U_i(S*_i, S*_{-i}) then
        U_i(S'_i, S*_{-i}) = U_i(S*_i, S*_{-i})
```

This paper uses the concept of Nash Equilibrium where no participants may change their strategy. If at all during the gateway selection any participant does not reach its maximum utility state; Nash Equilibrium no longer exists and hence the game starts again and eventually there will come a point where each of the gateway was selected such that Nash Equilibrium was established. Thus the gateways are selected such that each of the end devices' demands is met such that there is a Nash Equilibrium between the gateways [41].

2.3 Floyd-Warshall and Minimimax Algorithm

2.3.1 Background

Article [43] presents a gateway location selection method using Floyd-Warshall algorithm on a network of high density nodes. Floyd Warshall is an algorithm for finding shortest paths in a weighted graph with positive or negative edge weights but with no negative cycles[47]. The article being discussed focuses mainly on gateway location selection and traffic routing. Gateway location affects route length and the quality of the network. Traffic routing is a key element of IoT. There are several works on gateway location selection and traffic routing. Hydro [13], Hilow[10], Dymo-Low[12] routing protocols were developed for low power and lossy networks (L2N). BV4[8] was a geographical location based routing protocol for L2N. RPL is a distance vector and source routing protocol for lossy network systems with high packet transmission rates[23]. The paper [39] proposed an algorithm based on tree routing protocol. The algorithm first sets local minimas, takes them as roots and then determines the spanning tree by flooding process.While studying for the chosen gateway selection model, a few papers we came across gave the idea that maybe traffic routing using Floyd-Warshall can be further improved. Such as, using SAW(Simple Additive Weighting) method[42] where a route's congestion value and distance value are merged using SAW to find an optimal route or using Dijkstra with Floyd-Warshall to find a faster and shorter route [37]. The paper [32] proposed a modified Floyd-Warshall algorithm to implement IEEE802.1aq protocol.

2.3.2 Working principle of Floyd-Warshall & Minimax Algorithm

Omar Mahmood and Alexander Paramonov from the Department of Communication Networks and Data Transmission, The Bonch-Bruevich Saint-Petersburg State University of Telecommunications in Russia came up with a gateway location selection model that uses all pairs shortest path finding algorithm, Floyd-Warshall to calculate the shortest route between every possible pairs of nodes in a graph where the nodes work as either gateway or end device. Then from the distance matrix found using the Floyd-Warshall algorithm a gateway location is selected. To select the gateway, they used a minimax problem to select the gateway with the maximum length from every row and from these gateways, choose the gateway with the minimum distance to which all the data will be sent. The objective of this model is to shorten the route travelled for data delivery and improve traffic quality of the network. According to the authors, the most desirable gateway location is the one from which all network nodes are at a minimal distance and when translated into a graph, it is the center of the graph. This is the reason why their model used Floyd-Warshall algorithm and Minimax problem [43]. The parameters of this scheme are given in the below table.

Terms	**Definition**
dist	distance between network nodes
n	number of network nodes
e	number of end devices
g	number of gateways
GEdist	distance between end device and gateway
c_dist	distance between end device and chosen gateway
g_pos	index number of chosen gateway
min	min distance value of final chosen gateway
pos	final chosen gateway position

Table 2.3: Terms used in FWM algorithms

Floyd Warshall is an algorithm for finding shortest paths in a weighted graph with positive or negative edge weights but with no negative cycles[47]. The form of Floyd-Warshall currently recognized and used in this paper was published by Robert Floyd[4] in 1962. It is quite similar to the algorithms published by both Bernerd Roy[3] in 1959 and Stephen Warshall[5] in 1962. The algorithm is given below:

Algorithm 7 Floyd-Warshall Algorithm

input: dist, n
for $i = 0, 1, \ldots$n **do**
  for $j = 0, 1, \ldots$n **do**
    for $k = 0, 1, \ldots$n **do**
      if $dist[i][k] + dist[k][j] < dist[i][j]$ **then**
        $dist[i][j] = dist[i][k] + dist[k][j]$

Algorithm 8 Minimax Algorithm

```
input: GEdist, e, g
for i = 0, 1, ...e do
    for j = 0, 1, ...g do
        if c_dist[i] ≤ GEdist[i][j] then
            c_dist[i] = GEdist[i][j]
            g_pos[i] = j;
Output: min, pos
for i = 0, 1, ...n do
    if min > c[i] then
        min = c_dist[i]
        pos = g_pos[i];
```

To find the shortest path between i and j, another vertex k is considered. When the path from i to k and k to j is shorter than the original route of i to j, the shorter distance is considered as the new route between i and j vertices. After calculating the shortest path, the center of the graph is found using the Minimax Algorithm. Therefore the algorithms select the gateway which is approximately located at the center of the network.

2.4 Evolved Reliability and Traffic-aware gateway selection

2.4.1 Background

Mesh Network (MN) technology was first invented for military purpose and first-responder application, to give soldiers a reliable broadband communicating medium which is accessible from anywhere in the battlefield [11]. Since the early 2000s the technology became very well known in municipal wireless broadband networks[33]. MN modifies the idea of basic radio frequency (RF) physics to achieve greater coverage, throughput, flexibility and cost-efficiency [11]. In a MN each node can act as a router for other nodes in the network. The nodes are either a permanent server or a mobile device itself. Such highly connected infrastructure of MN makes it a very cost friendly mobile broadband network since transmission from each node does not have to be till the ultimate destination;it can be to the very next node itself. Since in MN each node is connected to many other nodes, if there is a hardware failure in one of the nodes it does not cause the entire system to fail. There are always several other routes through which transmission can take place. This property makes MN extremely reliable[11]. Mesh Networking is a ground-breaking innovation that has impacted the way 'wireless' network perform. It has revolutionized various real life applications starting from government, transportation to digital home and beyond. The promising feature of MN has also. In our research we decided to research on how Wireless Mesh Network (WMN) impacts the networking world and how it differs from the other three models.

There have been many proposed and existing work on Wireless Mesh Networks (WMN). For instance: Pandi, Wunderlich and Fitzek in [44] work on developing a WMN with reliable low latency by using the principal of opportunistic routing and network coding. They aim to turn the chaotic and dynamic WMN into a more stable structure regardless of various node failures and audience interaction. In another studies, Hattori,Kagawa,Yowada and Hamaguch in [24] proposed an energy-efficient model for mobile mesh networks. They focus on controlling the movement of nodes using two features: (1) the dynamic allocation of reference and moving nodes, and (2) the temporal variation of Received Signal Strength Indicator(RSSI). In our research we decided to study a model that focus on both reliable low latency, energy consumption; along with increasing reliability of all possible network paths.

2.4.2 Working principle of Evolved Reliability and Traffic-aware Gateway Selection

The ERTGS model prioritizes traffic demand and reliability of the path to select a gateway. In addition to that it optimizes energy consumption by replacing high energy consuming node with a low energy consuming node after some iterations and by clustering with the help of Genetic algorithm [33]. The parameters of this scheme are given in the below table.

Term	**Definition**
V	Set of all mesh nodes in the network
l	number of links in the interference range of node v
p	number of gateway candidates
Y_n	nth path between 2 nodes
TD	Traffic demand generated in the network
C	Set of IGCs
i	A selected node in V or C
j	All the gateway candidates in C except i
R	A threshold for the number of hops between 2 nodes
R_{ij}	Reliability of the path from nodes i to j using path tracing method
$Sum(i)$	Sum of reliability of node i to all the other IGCs
$T(i)$	Aggregate traffic in the interference range of node i
K‘	A list of nodes

Table 2.4: Terms used in ERTGS algorithms

In this model gateway is selected in a way so that MRs in high traffic areas get selected as gateways. In Algorithm 9 the aggregate traffic of each node is calculated. aggregate traffic refers to the total traffic in the interference range of a node. Based

Algorithm 9 IGC selection algorithm

Input V
Output C
for each $i \in V$ **do**
  $T(i) = \sum_{j} TD_j$
Sort $i\, in\, K^{'}\, according\ to\ T(i)$
Select $P\, of\, i\, in\, K^{'}\, with\ high\ T(i)$
$C \leftarrow i$

on the calculated aggregate demand, the nodes are sorted in descending manner. Then, nodes with high aggregate traffic demand are selected as IGCs. As a result the number of nodes considered for selecting gateways are narrowed down based on traffic. After considering the traffic of the network, the reliability of paths is calculated in Algorithm 10 to select IGWs. In Algorithm 11 m number of MRs are

Algorithm 10 IGW selection algorithm

Input V
Output A value for each IGC
for each $i \in C$ **do**
  for all paths from $i\ to\ j$ **do**
    if $Dqos \geq R$ **then**
      $R_{i,j} = P(Y_1 \cup Y_2 \cup Y_3, ..., \cup Y_n)$
      $Sum(i) = \sum R_{i,j}$

selected to be the gateways out of n nodes. Algorithm 9 and 10 are called from here to combine the whole process. Using equation(2.8) reliability $R_{i,j}$ is calculated. Here $R_{i,j}$ denotes the reliability of a route between ith and jth IGC. Y_n shows the paths between two IGCs with hop count less than 3. Next step is to sort the IGC again based on reliability and IGCs with high reliability are selected as gateways.

$$R_{i,j} = P(Y_1 \cup Y_2 \cup Y_3, ..., \cup Y_n) \tag{2.8}$$

Algorithm 11 IGW selection method:ERTGS

Input V
Output N IGWs
for each $i \in V$ **do**
  algorithm 1
for each $i \in C$ **do**
  algorithm 2
Select N of the nodes i having highest $Sum(i)$ as IGWs

Only a few IGCs are selected based on traffic and then among them finally m number of MRs are selected as Gateways based on reliability. However if the same node is considered as IGC and gets selected as IGW too many times it consumes a lot of energy.So to minimize that, after a certain number of simulation energy consumption of all the nodes are calculated and the node which is getting selected consecutively is replaced with a low energy consuming node. Equation (2.9) is used for energy consumption calculation.

$$E^i = E^i_{tr} + E^i_{re} + E^i_{id} \tag{2.9}$$

Here E^i_{tr} represents energy consumed in the transmission process and E^i_{re} Represents energy consumed while receiving packets of the ith node. E^i_{id} denotes the energy required at idle state. The data transmission occurs both between gateway to gateway and between gateway to other MRs. This is why to calculate energy consumption it is necessary to identify these connections. Utilizing the work of [33] energy consumption can be calculated using the equation (2.10). Here number of packets are considered where $A(v_i, v_k)$ represents the number of packets transmitted from ith node to kth node. $A(v_k, v_i)$ represents the number of packets received from kth node to ith node. In Algorithm 12 energy consumption optimization is applied.

$$E^i = \left(E^i_{tr} \sum_{k=1}^{n} A(v_i, v_k) \times U_{v_i,v_k} \right) + \left(E^i_{re} \sum_{k=1}^{n} A(v_k, v_i) \times U_{v_k,v_i} \right) + E^i_{id} \tag{2.10}$$

Algorithm 12 Energy consumption optimization

1: Determine the amount of consumed energy in the interference range of all the gateway candidates after a certain amount of iterations
2: Find the node with the lowest consumed energy among all the other nodes in the interference range of all the gateway candidates
3: Set the node as the gateway candidate
4: Repeat steps 2-4

Genetic algorithm (GA) is utilized for clustering the nodes the deletion criteria are given below:

1. A gateway can be connected to 4 mesh routers at most.
2. A mesh router can work as relay for 3 other MRs
3. Hop count of a selected path between an MR and a gateway cannot exceed 3

Algorithm 13 The clustering method

1: Connect all the MRs that can be connected to any IGW with a single hop
2: Deletion criteria exploiting GA for the nodes connected to more than one IGW
3: Connect the MRs that are not connected to any IGW and can be connected to an IGW with 2 hops
4: Repeat step 2
5: Connect the MRs that are not connected to any IGW and can be connected to an IGW with 3 hops
6: Repeat step 2

Paths with hop count 1 are assigned with lowest fitness value and paths with hop count three are assigned with highest fitness value. Paths with better fitness value have a higher chance of getting selected for cross over. The paths between nodes are considered as population. Binary encoding is used for chromosome encoding. when the hop count is 1 no crossover is required. However when paths with more hop counts become available, crossover between populations offers an optimal path between an MR and a gateway. After crossover some arbitrary changes are made in the offspring chromosome and if the newly generated path is better than the previous one , the previous path is replaced with the new path. Due to the implementation of GA to select cluster heads, all nodes do not have to be active at all times and that reduces energy consumption as well. Because of considering traffic and selecting gateways in high traffic areas, throughput increases and with energy consumption optimization and using Genetic Algorithm for clustering, energy consumption decreases. However, the reliability calculation involves evaluating all paths between two nodes. This is computationally heavy and may not be applicable for simpler hardware.

In the upcoming chapters we will discuss how we implemented the above models and the results we obtained from the implementations.

Chapter 3

Methodology and Approach

The focal point of this chapter is explaining our procedure of reaching the conclusion for our comparative study. For instance, how the network topology is built to simulate GTGWS, Taxi-Sharing , FWM and ERTGS models. The chapter also gives a clear insight on various criteria used for comparing these models. The process of running the simulations under different scenarios and various data collected during these simulations are elaborately described as well.

3.1 Research approach

To fulfill the main research objective which is to compare the selected models, a common ground for comparison has to be established first. To attain that, a network topology is built consisting of some gateways and devices where the models would be simulated. The network also has to be assigned with some characteristics to make the simulation as much close to the real world as possible such as latency, distance between the nodes, bandwidth etc. Besides, many of these assigned values are used in the gateway selection procedure of the selected models and the calculation process of evaluation criteria. After the network is ready each model is simulated in the network and their performance is observed. A large number of simulations are run for various scenarios so that the simulation data reflects most of the possible cases and gives better results. With each simulation different types of data related to the evaluation criteria are gathered and later these data are used to plot graphs which show visual comparison of the models.The diagram below shows the research approach.

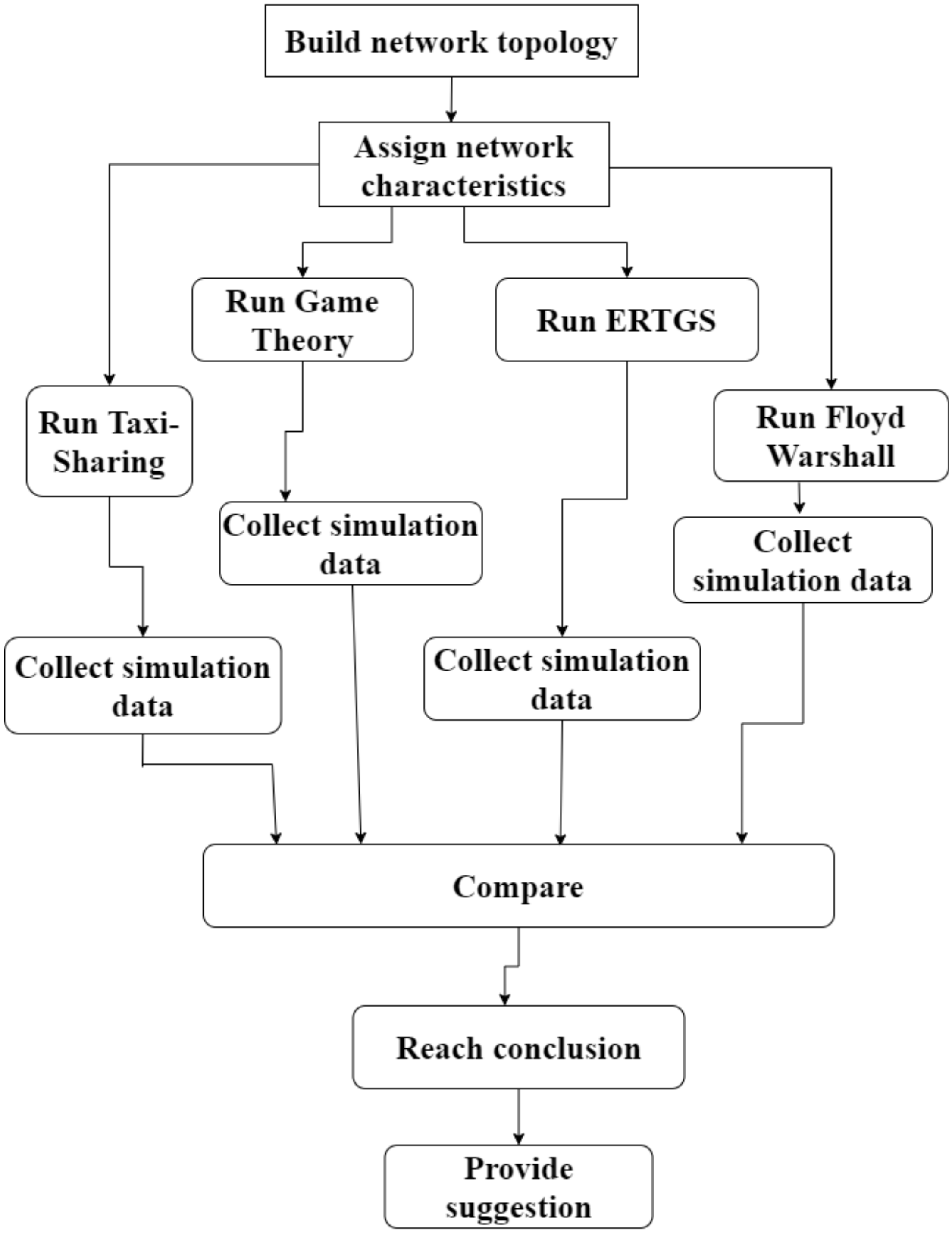

Figure 3.1: Research Approach

3.2 Network overview

3.2.1 Topology

To implement and evaluate the gateway selection models a network is required and so we define our network to be a Graph G(V, E). Vertices(V) represents a set of nodes that includes m number of gateways and n number of devices. Edges(E) denotes the connection between nodes. In Taxi-sharing and GTGWS, gateway functionalities are assumed to be fixed in specific nodes; this is why in this paper certain nodes are assigned to perform as m gateways in all simulations for these two models.

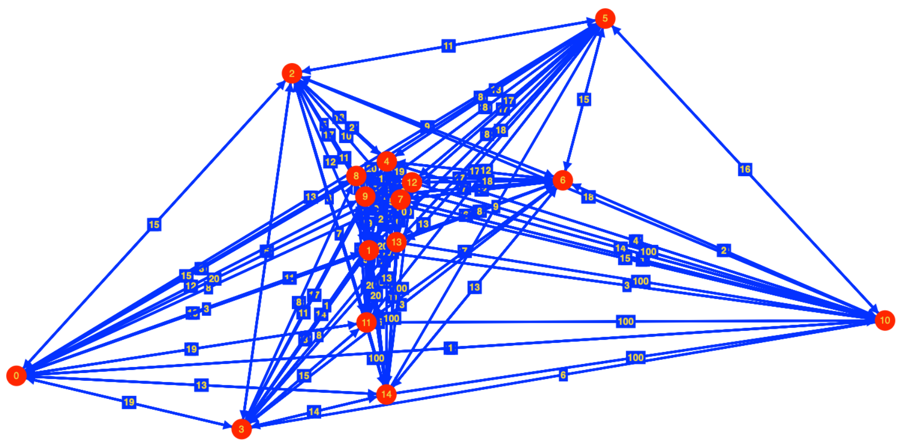

Figure 3.2: Network Topology for simulation

On the other hand, in ERTGS and FWM model, all nodes in V can be candidates to be selected as a gateway. After selecting m number of nodes, they are assigned with gateway functionalities and the rest of nodes n=V-m, work as devices who are using the gateways to connect to the internet. For this reason while implementing FWM and ERTGS model among all nodes, m nodes are selected to operate as gateways and gateway functionalities are assigned afterwards. To compare this with real life scenarios mobile phones and computers can be considered. They usually work as end devices but they can be turned into access points by assigning them those functionalities. In this paper we assume devices like these will work as only end devices for Taxi-sharing and GTGWS models whereas they can either operate as end device or gateway in FWM and ERTGS models.

3.2.2 Network characteristics

To turn this graph into a more realistic network, some characteristics have to be assigned. For our research- bandwidth, transmission cost, transmission and reception power, Packet size, distance between nodes etc are considered. Instead of assigning arbitrary values to these factors, information has been gathered from other sources to make the simulation feasible. The bandwidth, packet size information has been collected from [41]. The transmission and reception power has been assigned according to the information available in [33]. The cost of per MB transmission has been given [40] in RM which is converted into BDT and assigned accordingly and the information about distance between nodes is used form [43].

3.3 Evaluation criteria

3.3.1 Load Balancing

Load can be defined in many ways but in this simulation the incoming traffic is defined as load. The difference of loads among gateways is used as the parameter to evaluate load balancing in [41] and in this simulation as well the load difference is used. If the difference of load among gateways is low that would mean that load is distributed better among the gateways and the gateways are working at a similar level. On the other hand high load difference between nodes would mean some gateways are working too much whereas others are not utilizing their resources to the fullest. While evaluating the models in terms of load balancing, lower load difference would indicate better load balance and models showing high load difference would indicate they are not efficient enough in balancing load. Maximum possible load difference is 50 MBps, this occurs in case of a gateway that was not selected at all for data transmission. After 1000 simulation under various network conditions, average load balancing is recorded for each model. Average load difference percentage of the models are calculated using the equation (3.1)

$$Average\ Load\ Balancing\ \% = 100 - \left(\frac{Average\ Load\ Difference}{50MBps}\right) \times 100 \quad (3.1)$$

3.3.2 Throughput

Throughput is an important factor in IoT networks because high throughput would show the devices are communicating with each other rapidly. Obviously the IoT system would have to make some decisions based on the data it receives from the devices. High throughput would pace up this process which will make the overall IoT system to run a lot smoother and this is why throughput is considered as one of the evaluation criteria. Throughput can be calculated as packets per second or bits per second. Here bits per second is calculated first and then it is converted into MBps. The equation used to calculate throughput is:

$$Throughput = \frac{Successfully\ Transmitted\ Data}{Latency} \quad (3.2)$$

Here, network latency is assumed to be 65 ms for all gate-gate connection and 60 ms for all gate-end device connection. The aim of this research is to evaluate which model show higher throughput over the others. After 1000 simulation under various network conditions, average throughput is recorded for each model. Average throughput percentage of the models are calculated using the equation (3.2) where bandwidth is taken as 50 MBps.

$$\%\ of\ Average\ throughput = \left(\frac{Average\ Throughput}{Bandwidth}\right) \times 100 \quad (3.3)$$

3.3.3 Energy consumption

Energy consumption is highly linked to the cost of running the overall IoT system. As the energy consumption rises, so would the electricity bill. In a number of IoT scenarios, low energy consumption is preferred and so we evaluate which of the selected four models consumes less energy. Energy consumption of each node is calculated with the help of the equation below. In [33] same equation was used to calculate energy consumption for ERTGS model.We are using the following equation to calculate the energy consumption for all the four models.

$$E^i = E^i_{tr} + E^i_{re} + E^i_{id} \tag{3.4}$$

Here E^i_{tr} represents energy consumed in the transmission process and E^i_{re} Represents energy consumed while receiving packets of the ith node. E^i_{id} denotes the energy required at idle state.

3.3.4 Energy consumption-Throughput ratio

With increasing throughput, the energy consumption is bound to increase. So models with high throughput will consume high energy whereas models with lower throughput will consume low energy. So, only evaluating energy consumption and throughput separately will not show the energy consumption optimization level fairly. In [9] a ratio of total energy consumption and throughput has been used. For our study we will also use this criteria for the evaluation.

$$Energy\ to\ throughput\ ratio = \frac{total\ energy\ consumed}{average\ throughput} \tag{3.5}$$

3.4 Simulation Set-up

The simulation process is divided into two segments:

1. Demand of end devices are kept within the fixed range of 1-15 MBps while the number of end devices in the network varies. For every variation the simulation is repeated 1000 times and the average value is recorded.

2. Number of end devices is kept at a fixed number of 50 while varying the ranges of demand of the nodes. For every variation the simulation is repeated 1000 times and the average value is recorded.

For example we set the number of devices to be 50 and the end device demand ranges for 1-15mbps. All the other characteristics of the network remain the same. Under this circumstance GTGWS Algorithm is run 1000 times. In a similar way it is simulated for 80 and 100 devices. Again to observe how the model performs when the demand of end devices varies from 1-15 MBps, 15-20 MBps, 20-25 MBps and 25-30 MBps and in these scenarios end device number is kept 50. The same process is done to Taxi Sharing, FWM and ERTGS models and the simulation data is collected.

To evaluate the models, a wireless mesh network is established with a bandwidth of 50 MBps. The packet size for sending data from the end device to Gateway is fixed at 50 KB. However, in Taxi-sharing models 'Hello' packets, 'Acknowledgement' packets etc are sent as well along with data packets. These packets are significantly smaller than the main data packets. The number of gateways is fixed at 5 for each scenario of simulation. To transmit and receive a packet, a fixed amount of power is consumed. Following table contains the details of all the network parameters considered in this research.

Transmission Range	100 m
Bandwidth	50 MBps
Number of Gateways	5
Packet size	50 KB
Transmission power	$2{\times}10^{-5}W$
Receiving power	$2{\times}10^{-5}W$

Table 3.1: Network Parameters

Other than above mentioned characteristics, few more assumptions are been made which are specifically required for Taxi-sharing models but not necessary for other models to run. The data transmission cost kept at 0.43 to 0.35 taka per Mb. The mentioned transmission cost in [40] has been converted to BDT from RM for this simulation. Maximum queue length of Gateways has been assigned to be 50 MB which allows each gateway to store 1000 packets at a given time. The deadline of the data packets are assigned at the range of 1 to 5 seconds. For implementation of the GTGWS model, the path loss value is 2 and alpha value is 1.

At the distance of 1 meter from gateways, maximum signal intensity is found. These values are mentioned in [41] and according to that these have been assigned to the network.For the implementation of ERTGS the number of devices that can connect to one Gateway is 3 and the maximum hop count of the selected path between a device and a gateway is also kept 3. A device can serve as a relay to 4 other devices. All these values has been assigned based on the implementation done in [33]. After establishing the topology, the four models are implemented in that topology in different scenarios to study the behaviour of these models in those scenarios. A number of simulations are run for each scenario and data about the network behaviour The evaluation criteria are mainly load balancing, throughput and energy consumption. However, with rising throughput energy consumption will generally rise [16]. To understand how much the models can optimize the throughput- energy consumption trade-off, a ratio of total energy consumption and throughput is also calculated [16].

the flowchart of the simulation process is as follows:

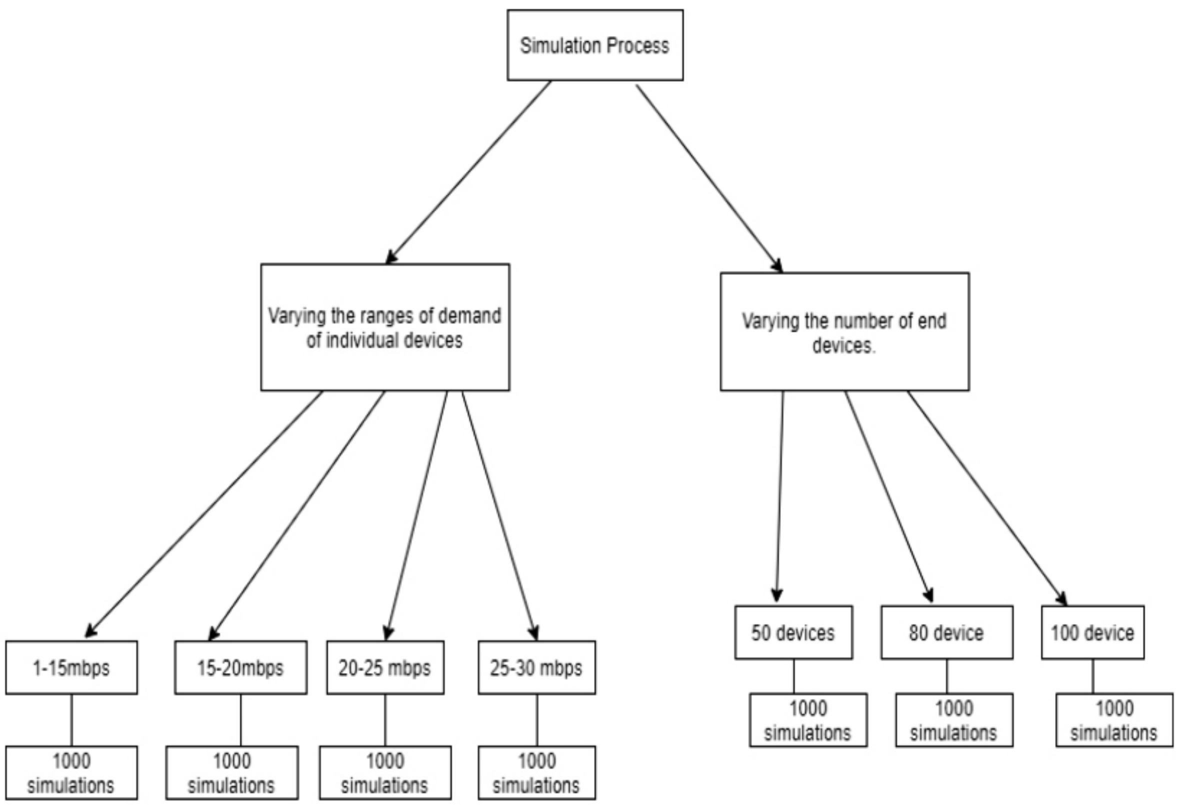

Figure 3.3: Simulation Process

3.5 Data collection

Throughput: To thoroughly evaluate we collect the data of average throughput. This gives an idea about how fast the communication among devices can occur in the usual case and in best case scenario.

Load balancing: Similar to throughput, for Load Balancing maximum and average load difference data is collected. Here maximum load difference shows the usual load balancing situation whereas maximum load difference the worst case scenario.

- Maximum load difference (Mbps):The maximum difference of load between two gateways found in the network in each simulation is collected.
- Average load difference (Mbps): The average of load differences among all gateways of the network is calculated and collected in every simulation.

Energy-consumption: Total energy consumption of the whole network would help further researchers to anticipate energy consumption if they are trying to implement these models with hardware and budget accordingly. Maximum energy consumption of the gateways show in worst case how much a gateway will consume and if it is feasible for their choice of hardware configuration of gateway.

- Total energy consumption(Joule): The total energy consumed by the network including all the gateways and devices is collected at every simulation.

- Maximum energy consumption(Joule): Maximum amount of energy consumed by a gateway at every simulation is collected.

Energy consumption to throughput ratio: After collecting the above mentioned data total energy and average throughput is used to calculate energy consumption to throughput ratio. The unit of this ratio is Js/Mb. Higher value of this ratio would mean the trade-off is not very optimized and lower value means the model offers high throughput compared to how much energy it is consuming.

3.6 Storing data and plotting graph

All the simulation data of each model in each scenario is collected in an organized manner to compare. Average of 1000 simulations for each criteria like throughput, load difference are calculated for each scenario. Using the average values, graphs are plotted which gives a visual representation of the comparison.

After plotting the graphs we analyze the result and reach a conclusion about which models are performing better based on the selected criteria. It is not possible to find one best model which surpasses all the other ones in all parameters. However, one model may do better in terms of throughput whereas another may provide better load balancing. After understanding the strengths of all the models we provide suggestions about application of these models in various real life IoT situations based on the priority of that situation. If someone is building a network where high throughput is a priority, the model which provides the highest throughput among all four is suggested. In this way we conclude our research by contributing to further research on this area by reducing the analysis needed to choose and implement any of these models.

Chapter 4

Implementation and Result Analysis

In this research, we studied four different types of gateway selection models for IoT-GTGWS, FWM, Taxi Sharing and ERTGS. GTGWS proposed an algorithm based on the concept of Game Theory. In this model the gateway is selected based on the concept of Nash Equilibrium and Maximum Utility[41]. FWM proposed a selection scheme which selects the gateway that is located at the center of the service area so that every device traverses the shortest distance possible[43]. Taxi-Sharing chooses active gateways and uses the concept of delay tolerant data and data compression during data transmission[40]. Lastly, ERTGS proposed a selection model based on the concept of Genetic Algorithm and reliability, using various combinations of algorithms[33]. The aim of this research is to implement these four models under different scenarios to evaluate their performances.

The evaluation criteria are: Throughput, Energy-Consumption, Load-Balancing and Energy-Consumption to Throughput ratio. The models are implemented under two different network conditions:

1. Network Condition I: Fixed number of end devices (50 nodes) while the demand of the end devices varies.
2. Network Condition II: The demand of the end devices have a fixed range of1-15 MBps; while the number of end devices vary from 50, 80 and 100.

When the number of devices is 50 and demand range is 1-15 MBps it can be considered the least congested scenario for this simulation. On the other hand for Network Condition I, the demand range 25-30 MBps is considered the most congested scenario and in Network Condition II, when the number of devices is 100 it is considered the most congested scenario. Under each network conditions, all four models are simulated 1000 times and the average results are tabulated to obtain graphs. In the rest of the part of this chapter the results obtained from the implementation will be discussed and analysed.

4.1 Evaluation in terms of Average Throughput

In this section we are going to look into what happens to the average throughput of the four models under two different network conditions.

Network Condition I : Fixed number of end devices (50 nodes) while the demand of the end devices varies. The table below shows the data obtained for average throughput of the four models.

	GTGWS	FWM	Taxi-Sharing	ERTGS
1-15 MBps	10.874	6.274	7.6294	15.323
15-20MBps	10.914	3.104	16.461	20.541
20-25 mpbs	15.032	2.915	21.282	25.687
25-30MBps	15.07	2	25.893	29.901

Table 4.1: Datasets of Average Throughput for 50 end devices

The graph below shows the curve obtained for average throughput of the four models.

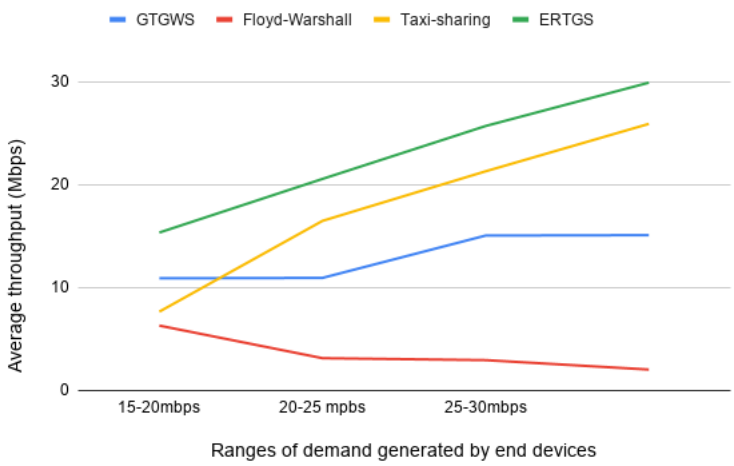

Figure 4.1: Average Throughput Graph for 50 end devices

Network Condition II : The demand of the end devices have a fixed range of 1-15 MBps; while the number of end devices vary from 50, 80 and 100.The table below shows the data obtained for average throughput of the four models under such condition.

	GTGWS	FWM	Taxi-Sharing	ERTGS
50 Device	10.874	6.274	7.6294	15.32
80 Device	6.403	3.922	7.609	14.99
100 Device	5.053	3.132	7.646	14.87

Table 4.2: Datasets for Average Throughput under fixed demand

The bar graph below shows the results obtained for average throughput of the four models under fixed demand.

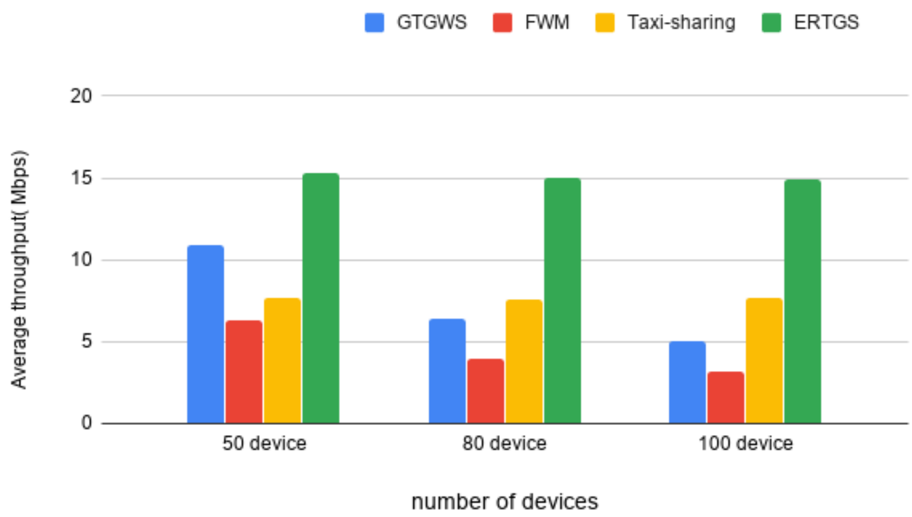

Figure 4.2: Average Throughput Graph under fixed demand

We can clearly see from the results obtained above, that ERTGS perform significantly better than the other models in terms of providing high average throughput due to the prioritization of traffic during gateway selection. Since gateways are being selected in high traffic areas, high volume of data transmission is occurring and so the throughput is very high in ERTGS. In taxi sharing maximizing throughput is not a priority. The gateways communicate with each other to evenly distribute the traffic and so in most cases the throughput remains in the mid level or lower level of traffic demand range. However, to go from 1-15 MBbs range to 20-25 MBps range there is a big difference compared to other ranges. In the first case the throughput would be around 7-8 MBps whereas in the second case the throughput is usually around 21.5-22.5 MBps. This is why initially the growth rate of throughput for taxi sharing is high but afterwards it does not grow that rapidly.

Individually Taxi-sharing and ERTGS is not affected much by the number of devices but the amount of demand affects them whereas GTGWS and FWM are highly affected by both the number of devices and the demand generation rate. The FWM model chooses one gateway per simulation. Which is why, the gateway fails to hold all the data a device transmits and so the average throughput decreases as demand rises. In the case of GTGWS, some gateways stay inactive and so the network cannot reach its full potential in data transmission. For this reason, average throughput is somewhat lower than Taxi-Sharing and ERTGS.

In the least congested scenario ERTGS utilizes 30.464% of total bandwidth whereas taxi sharing utilizes 15.25% of total bandwidth. FWM can reach 12.5% and GT-GTWS can reach 21.68% of the total bandwidth in least congested scenario. In the most congested scenario of Network Condition I, ERTGS utilizes 59.802% and in the most congested scenario of network condition ii, ERTGS utilizes 29.74%. Taxi sharing reaches 15.3% in Network Condition II and 51.7% in Network Condition I of total bandwidth. On the other hand, Game theory utilizes 30.14% Network Condition I and 10.106% in Network Condition II and Floyd Warshall utilizes 4%

in Network Condition I and 6.264% in Condition II of total bandwidth in most congested scenarios. The average throughput gradually rises with the increase of traffic demand for all three models as there is more data to transmit except FWM because it only selects one gateway for the whole network.

4.2 Evaluation in terms of Load-balancing

4.2.1 Average Load Difference

In this section we are going to look into what happens to the average load difference of the four models under two different network conditions.

Network Condition I : Fixed number of end devices (50 nodes) while the demand of the end devices varies. The table below shows the data obtained for average load difference for 50 end devices of the four models.

	GTGWS	FWM	Taxi-Sharing	ERTGS
1-15 MBps	23.724	50	2.5964	5.16
15-20MBps	23.957	50	4.968	6.907
20-25 mpbs	23.868	50	6.53	8.62
25-30MBps	23.868	50	7.771	10.347

Table 4.3: Datasets for Average load difference for 50 end devices

The graph below shows the curve obtained for average load difference for 50 end devices of the four models.

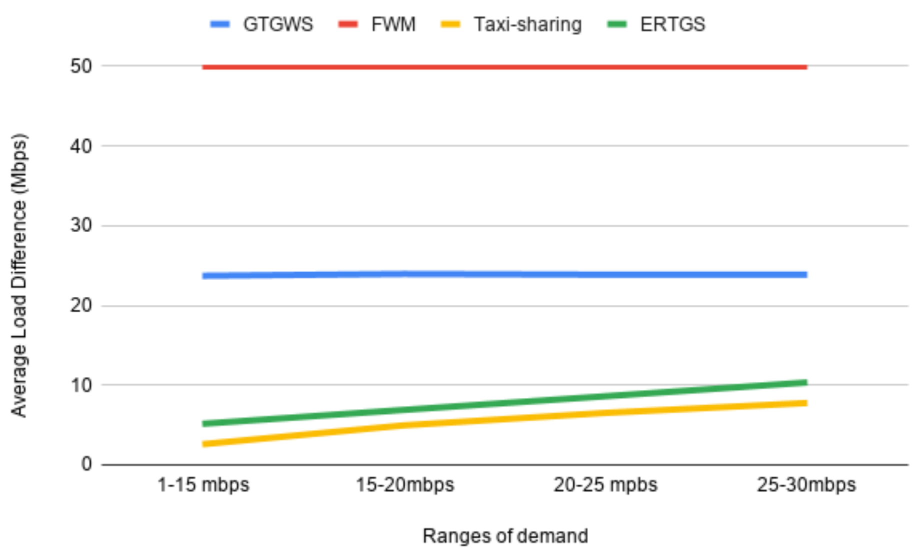

Figure 4.3: Average load difference graph for 50 end devices

Network Condition II : The demand of the end devices have a fixed range of 1-15 MBps; while the number of end devices vary from 50, 80 and 100.The table below shows the data obtained for average load difference of the four models under such condition.

	GTGWS	FWM	Taxi-Sharing	ERTGS
50 Device	23.724	50	2.596	5.161
80 Device	23.986	50	3.329	7.727
100 Device	23.996	50	3.832	5.173

Table 4.4: Datasets for Average load difference under fixed demand

The bar graph below shows the results obtained for average load difference of the four models under fixed demand.

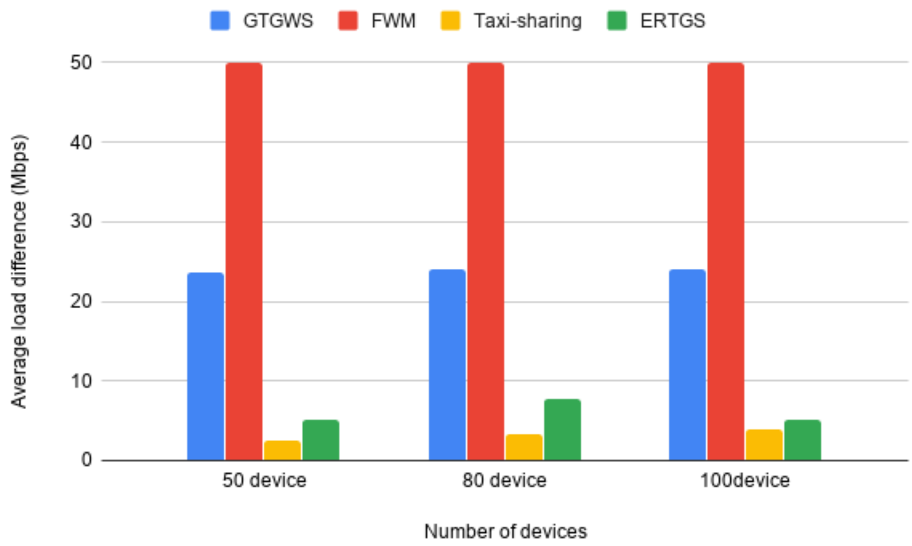

Figure 4.4: Average load difference under fixed demand

The load difference stays stable for GTGWS and FWM for different ranges of demand. However, even though the load difference in Taxi-Sharing and ERTGS rises with the increase in demand, they still provide lower average load difference than the other two models. In the case of a variable number of devices as well, Taxi-sharing shows the lowest amount of load difference. The gateways in the taxi sharing model communicate with each other and distribute the total load among them based on queue space and deadline of the data. This is why in average the load difference among gateways is very low in this model. In ERTGS, load balancing is not a priority but since it focuses on selecting gateways on high traffic areas. Some times more than one gateway might get selected in a specific area of the network so that high traffic can be handled properly whereas in low traffic areas the nodes are connected to relays or there is only one gateway.

Because of prioritizing traffic even though the load difference in ERTGS is not as low as taxi-sharing, it is still lower than other two models.the load difference keeps increasing uniformly with higher number of devices and higher traffic demand. This is because as the amount of data to be transmitted increases, it becomes more difficult to evenly distribute the load. Still the load difference of Taxi sharing remains lowest among all even in the most congested scenarios.

The load difference of GTGWS and FWM stays stable because FWM has just one active gateway and GTGWS always has inactive gateways and non-uniform load distribution that averages out similarly in every case whereas the load difference of Taxi-sharing and ERTGS varies. Since FWM only selects one gateway which alone takes 100% load from all devices possible, there is no load-balancing aspect and it has 0% load balancing in all cases. However, Taxi-sharing shows 94.8% in the least congested scenario. In most congested scenarios in network condition I it shows 84.458% and in network condition II 92.336%. GTGWS shows very similar results in most cases- 52.552%(least congested scenario), 52.264%(most congested scenario, network condition I) and 52.008%(most congested scenario, network condition II). ERTGS succeeded to balance 89.68% of load in the least congested scenario. In most congested scenario, network condition-i, it shows 79.306% of load balance and in the most congested scenario, network condition-ii it shows 89.654%.

4.2.2 Maximum Load Difference

In this section we are going to look into what happens to the maximum load difference of the four models under two different network conditions.

Network Condition I : Fixed number of end devices (50 nodes) while the demand of the end devices varies.The table below shows the data obtained for maximum load difference of the four models.

	GTGWS	FWM	Taxi-Sharing	ERTGS
1-15 MBps	23.724	50	2.5964	5.16
15-20MBps	23.957	50	4.968	6.907
20-25 mpbs	23.868	50	6.53	8.62
25-30MBps	23.868	50	7.771	10.347

Table 4.5: Datasets for Average load difference for 50 end devices

The graph below shows the curve obtained for maximum load difference of the four models.

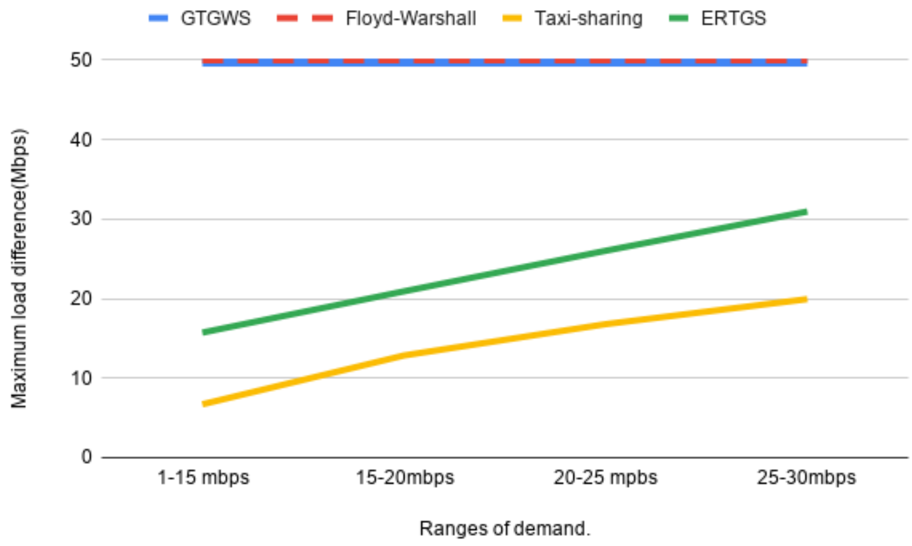

Figure 4.5: Maximum load difference Graph for 50 end devices

Network Condition II : The demand of the end devices have a fixed range of 1-15 MBps; while the number of end devices vary from 50, 80 and 100.The table below shows the data obtained for maximum load difference of the four models under such condition.

	GTGWS	FWM	Taxi-Sharing	ERTGS
50 Device	49.986	50	6.71587	15.734
80 Device	50	50	8.53	23.896
100 Device	50	50	9.9211	17.185

Table 4.6: Datasets for Maximum load difference under fixed demand

The bar graph below shows the results obtained for Maximum load difference of the four models under fixed demand.

The maximum load difference is the same for GTGWS and FWM for both various ranges of demand and number of devices. This is because during the selection process some of the gateways do not get selected while some get selected and reach their maximum bandwidth of 50 MBps; as a result the load on the unselected gateway(s) remain 0 MBps, while the load on the selected gateway reaches the maximum limit of 50 MBps. Thereby making the maximum load difference between some gateways as 50 MBps. Similar to the average load difference, here also Taxi-sharing shows the lowest amount of load difference. Before transmitting the actual sensor or end device data, the gateways communicate with one another and distribute the data to be sent accordingly in this model. This is why at a certain time there is usually a lower difference of load among gateways.

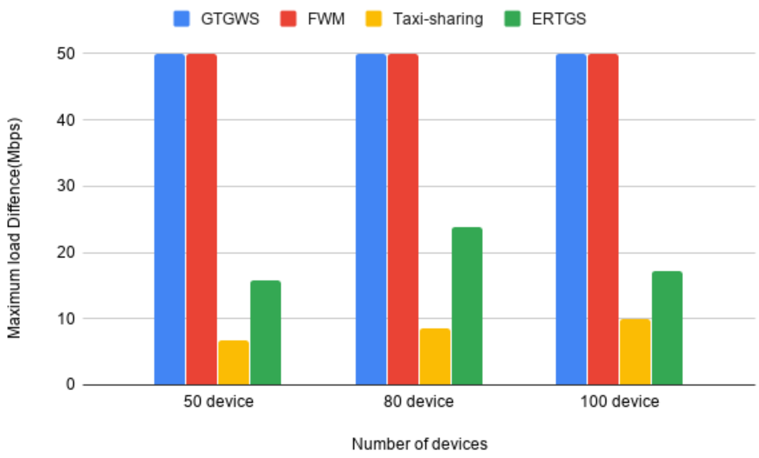

Figure 4.6: Graph for Maximum load difference under fixed demand

4.3 Evaluation in terms of Energy consumption

4.3.1 Total Energy consumption

In this section we are going to look into what happens to the Total Energy consumption of the four models under two different network conditions.

Network Condition I : Fixed number of end devices (50 nodes) while the demand of the end devices varies. The table below shows the data obtained for Total Energy consumption for 50 end devices of the four models.

	GTGWS	FWM	Taxi-Sharing	ERTGS
1-15 MBps	102.606	52.695	398.855	397.16
15-20MBps	102.671	52.695	422.5387	530.2465
20-25 mpbs	102.028	52.695	435.032	662.033
25-30MBps	101.685	52.695	447.5265	796.756

Table 4.7: Datasets for Total Energy consumption for 50 end devices

The graph below shows the curve obtained for Total Energy consumption for 50 end devices of the four models.

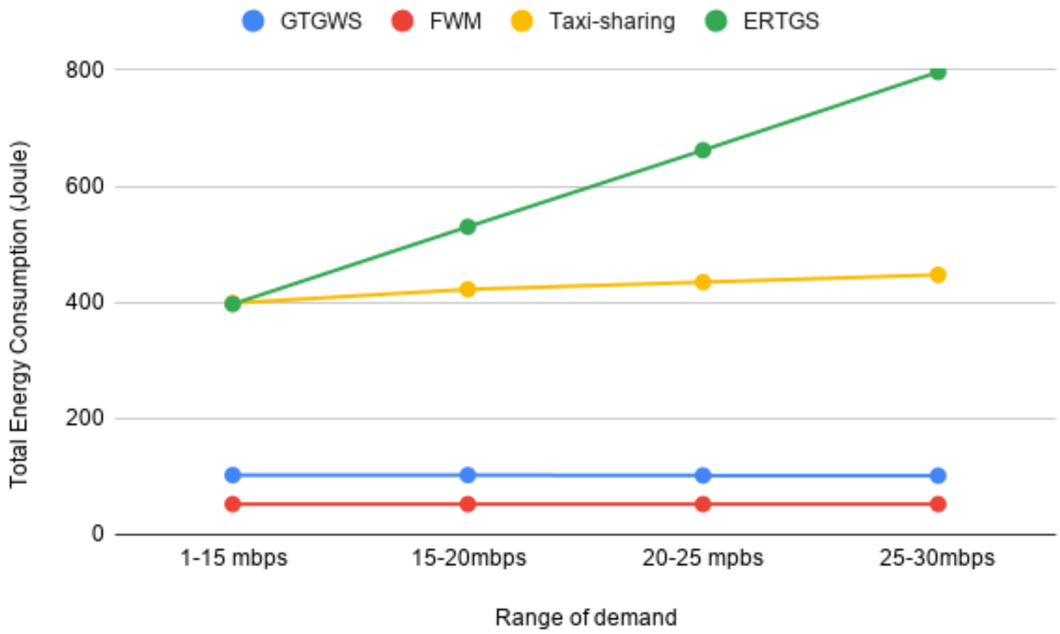

Figure 4.7: Total Energy consumption graph for 50 end devices

Network Condition II : The demand of the end devices have a fixed range of 1-15 MBps; while the number of end devices vary from 50, 80 and 100.The table below shows the data obtained for Total Energy consumption of the four models under such condition.

	GTGWS	FWM	Taxi-Sharing	ERTGS
50 Devices	102.606	52.695	398.855	397.16
80 Devices	104.086	54.165	413.041	629.1425
100 Devices	105.118	55.145	422.7728	781.4685

Table 4.8: Datasets for Total Energy consumption under fixed demand

The bar graph below shows the results obtained for Total Energy consumption of the four models under fixed demand.

The total energy consumption stays very stable in all three models except ERTGS. This is because of the rise of throughput in this model with the increase of demand. As the throughput grows faster, so does the total energy consumption of the network. The total energy consumption of ERTGS is very similar to Taxi-sharing when there is 50 devices however it increases highly with the increasing number of devices. When there is higher number of devices with high throughput, the number of packets transmitted in the overall network increases. Since the energy consumption is dependent on the total number of packets, the ERTGS consumes the most energy. Also the devices working as relays have to consume extra energy to transmit the data packets from neighbors. Many devices are working as relays in this model which adds up to the total energy. In Taxi sharing the devices are only sending data as per their own demand. They are not carrying forward data from other devices. So

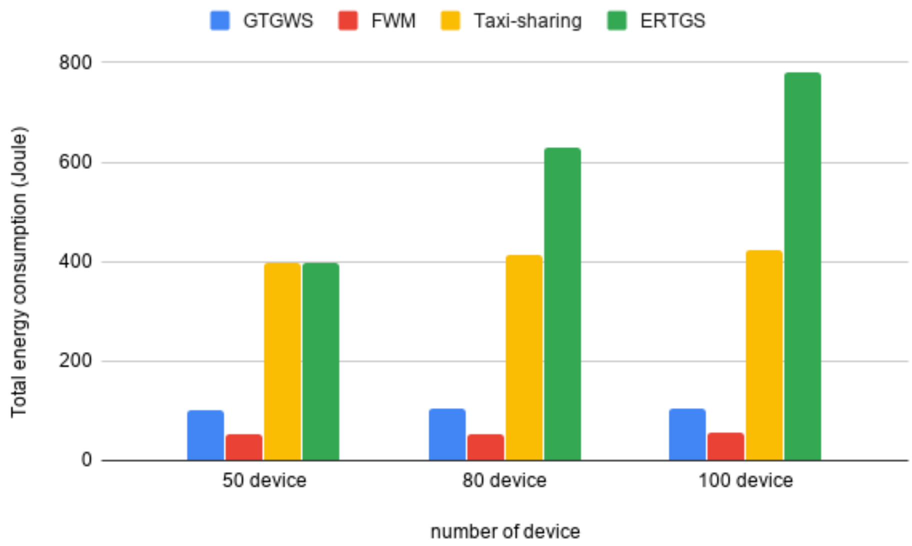

Figure 4.8: Total Energy consumption Graph under fixed demand

the main energy consumption in the network is happening among gateways. Since there are a large number of devices compared to gateways and the devices consume much less energy in taxi sharing models compared to ERTGS, the total energy consumption in the network is lower than ERTGS. In FWM, only one gate is active so the data transmission is low and so energy consumption is lower than the rest. In GTGWS, while many gates are active, some gates have high transmission rate and some gates have low transmission rate. This uneven transmission is the reason why Energy consumption is medium.

4.3.2 Maximum energy consumption

In this section we are going to look into what happens to the Maximum energy consumption of the four models under two different network conditions.

Network Condition I : Fixed number of end devices (50 nodes) while the demand of the end devices varies. The table below shows the data obtained for Maximum energy consumption of the four models.

	GTGWS	FWM	Taxi-Sharing	ERTGS
1-15 MBps	25.049	25.049	76.182	13.533
15-20MBps	25.049	25.049	81.332	18.2185
20-25 mpbs	25.049	25.049	83.081	22.824
25-30MBps	25.049	25.049	84.7265	27.5505

Table 4.9: Datasets for Maximum energy consumption for 50 end devices

The graph below shows the curve obtained for Maximum energy consumption of the four models.

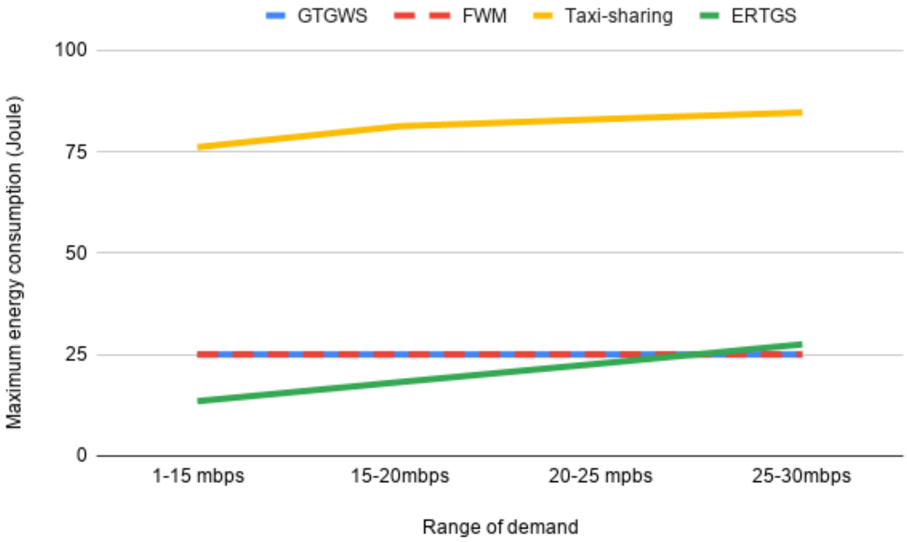

Figure 4.9: Graph for Maximum energy consumption for 50 end devices

Network Condition II : The demand of the end devices have a fixed range of 1-15 MBps; while the number of end devices vary from 50, 80 and 100.The table below shows the data obtained for Maximum energy consumption of the four models under such condition.

	GTGWS	FWM	Taxi-Sharing	ERTGS
50 Device	25.049	25.049	78.182	13.533
80 Device	25.049	25.049	79.81	18.498
100 Device	25.049	25.049	81.003	15.2845

Table 4.10: Datasets for Maximum energy consumption under fixed demand

The bar graph below shows the results obtained for Maximum energy consumption of the four models under fixed demand.

When it comes to the maximum amount of energy consumed by a device, Taxi-sharing consumes the most energy compared to other models. The maximum energy consumed by GTGWS and FWM overlaps. The maximum energy consumed by ERTGS stays the lowest upto 25 MBps of demand but after that it grows higher than GTGWS and FWM. When the number of devices varies in those cases also Taxi-sharing has the highest value of maximum energy consumption. Even though total energy consumption of Taxi-sharing was lower than ERTGS, at a certain time the maximum energy consumption by a gateway is much higher. This show, some gateways are not consuming much energy but few of them consuming very high amounts of energy.

This is because in Taxi-sharing model the gateways communicate with one another before sending packets and in this process some gateways are getting more requests from their neighbors than others and these add up. In addition to that, while communicating with other gateways and end devices, the gateways are compressing

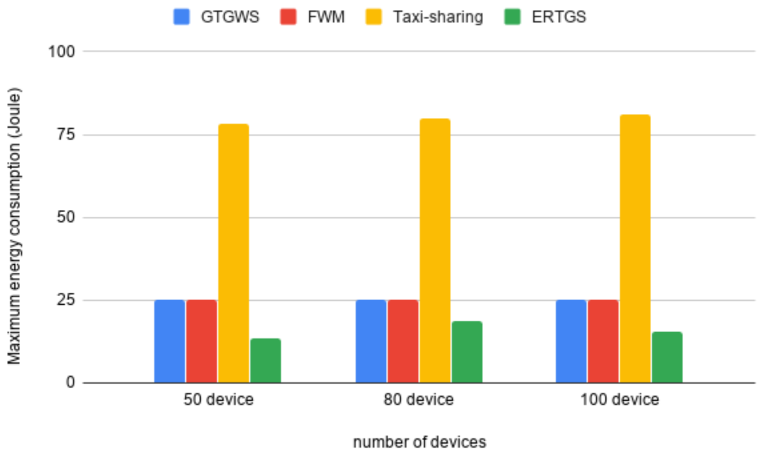

Figure 4.10: Graph for Maximum energy consumption under fixed demand

data to send to the cloud. Some gateways may not have to send much of their own data via other gateways which contributes to lower load difference because the incoming traffic decreases. However that particular gateway is compressing a higher amount of data which causes its individual energy consumption to become very high. This shows that Taxi- sharing is not very energy-efficient.

On the other hand ERTGS had the highest amount of total energy consumption but at a given time the maximum energy consumed by a device in the network is the lowest among all. This model utilizes GA for clustering, As a result most nodes are communicating with cluster heads and finally the cluster heads send data to the selected gateways. So, the gateways are idle when they are not communicating with cluster heads and the cluster heads are busy accumulating data of the cluster. This is why the maximum energy consumed by a gateway does not reach very high. This shows that most of the gateways are consuming a similar range of energy. Their technique of replacing an Internet Gateway Candidate after a few simulations with a node which has consumed the least amount of energy prevents one Gateway to consume too much energy.

4.4 Evaluation in terms of Energy to throughput ratio(Js/Mb)

The results in the table below show that no model can provide a similar level of energy consumption to throughput ratio for both the cases of changing number of devices and different demand ranges. When the number of devices are varying, FWM provides the lowest values of the ratio which means it has the most energy consumption-to throughput trade off optimization whereas in case of different data demand rangers GTGWS performs the best. Even between Taxi sharing and ERTGS, When it comes to different numbers of devices, ERTGS has lower values but in case of various ranges of demand, initially the value of Taxi-sharing is still higher but it gradually goes down whereas the values of ERTGS are rising.

However it is clear that when it comes to balancing throughput and energy consumption, Taxi-sharing is not performing well compared to other three models. Although

Network Condition	Parameters	GTGWS	FWM	Taxi-Sharing	ERTGS
Different Number of Devices	50 End Devices	9.436	8.398	52.278	23.966
	80 End Devices	16.256	13.81055	54.283	41.97
	100 End Devices	20.803	17.606	55.29	52.55336
Different Ranges of Demand	1-15 MBps	9.436	8.396	52.27	15.32
	15-20 MBps	9.407	16.976	25.669	20.541
	20-25 MBps	6.787	18.077	20.441	25.687
	25-30 MBps	6.747	26.3475	17.28	29.901

Table 4.11: Data for Energy to Throughput ratio

FWM shows lower values but it has to be kept in mind that FWM only selects one gateway and there is only so much energy it can consume at a given time whereas GTGWS selects multiple gateways. FWM can be a great choice for smaller networks where energy consumption has to be optimized and very high throughput is not required. Since GTGWS shows lowest value in one scenario and in the other it is significantly lower than Taxi-sharing and ERTGS and very close to the values of FWM, it can be said that GTGWS provides highest energy consumption-throughput optimization.

4.5 Summary of the Analysis

The summary of the analysis is given in the table below. As we have learned from [41][16][9]In a network with High Throughput; lower load difference and energy-throughput ratio is preferable.

	Models			
	GTGWS	FWM	Tax-Sharing	ERTGS
Throughput	Medium	Low	Moderately High	High
Load Difference	Moderately High	High	Low	Medium
Energy Consumption	Medium	Low	High	Moderately High
Energy-Throughput Ratio	Low	Medium	High	Moderately High

Table 4.12: Performance comparison of different IoT Gateway Selection Models

- Highest outcome is denoted as - **High**
- Slight lower than the 'Highest' outcome - **Moderately High**

- Outcome lower than ‘Moderately High’ - **Medium**
- Lowest outcome of all the outcomes - **Low**

4.6 Analysis & Suggestions

The results of this research suggest that different models perform well under different circumstances. In Chapter 2, we learned that IoT doesn’t follow a ‘standard’ protocol for gateway selection; It has different selection schemes for different applications. This is mainly due to the fact that some applications give priority to a specific network criterion over others. Based on the results we obtained from our research we are offering a suggestion in the table below for GTGWS, Taxi-Sharing, FWM and ERTGS. Table 5.1 shows which model performs comparatively better for a specific criterion.

Priority	**Preferred Model**
High Throughput	ERTGS
Low Energy Consumption	FWM
Efficient Load Balancing	Taxi-Sharing
Optimized Trade-Off Between Throughput and Energy Consumption	GTGWS

Table 4.13: Preferred Model Based on Priority of the IoT Application

In some networks very high throughput can be of top priority such as live streaming or large security networks. If the data does not reach in time quality can be reduced where live video or audio streaming is occurring. Every minute can be precious in large security systems and data needs to be available on time but energy consumption may not be as important and the owners may be willing to trade energy efficiency for higher throughput. For these kinds of situations, ERTGS models can be used since they offer high throughput.

On the other hand in some cases high throughput may not be as important. In space research the researchers do not need to know about incoming data from space right away. They collect the data over a long period and then conduct research. In these scenarios Taxi-sharing model can be utilized since it works with delay tolerant data. Also a large volume of data will have to be received which means load balancing is highly important in these cases and taxi-sharing showed the most efficient load balancing. Besides, even though throughput in the taxi sharing model is not as high as ERTGS it was significantly higher than the other two which means it provides sufficient throughput so that the research would not be hampered

In healthcare, agricultural application of IoT gateway requires low energy consumption but the messages also need to be sent timely. Often patients wear devices which create Wireless Body Area Network (WBANs) and these networks require low energy consumption. If the patient needs to charge the device again and again then it is not of much use. Based on the health condition the device may send a message to the doctor or a close relative. So, the message needs to be sent timely also. Since Game theory offers the most energy consumption- throughput trade-off optimization, it can be used in these scenarios. In agriculture also the sensors are collecting data from the environment and sending messages when necessary. Since the data is not as high volume as complex research or monitoring a whole city, throughput offered by game theory can be enough and the low energy consumption compared to the throughput offered is helpful in these scenarios where continuous source of power is not always available.

Other than complex applications of IoT sometimes simple applications are also helpful in our lives. Small alarm systems for someone's home or garage, car parking systems etc do not require very high throughput or load balancing. However, nobody would want to spend much on electricity bills for these small projects and so very low energy consumption would be top priority here. Since FWM offers lowest energy-consumption it can be used in scenarios like these.

Chapter 5

Conclusion & Future Work

Our research focused on four very different models for gateway selection that could be used in IoT. All of these four models were very much different from one another and each proposed different ways of gateway selection to enhance network performance. We intended to carry out a comparative analysis to figure out which one of these four models show promising outcome on the basis of mainly three criteria: high throughput, low energy consumption and efficient load balancing during data transmission. From our study we found out that none of these four models can provide groundbreaking results for all three criteria in a given scenario. For instance, Tax-Sharing Gateway Selection Model show impressive load balancing compared to the other three models. While it performs poorly when it comes to low energy consumption. On the other hand, FWM performs very well in terms low energy consumption but it's throughput level is not very impressive and is the lowest among the four models. ERTGS model has a very high throughput but it's energy consumption rate is higher than GTGWS and FWM. As for GTGWS model, it showed a moderate level of network throughput but performs poorly in terms of load balancing compared to Taxi-Sharing and ERTGS. Therefore, although these four models proposed ways for efficient gateway selection; when compared with other models it can be seen that, none of the model have impressive overall efficiency. However, it is necessary to mention that there were many limitations and assumption involved in our research and it is possible that the results we derived could deviate from a real life scenario.

In future we aim to focus on running the simulation on a more realistic topology to derive reliable and accurate results.We also want to take our comparative analysis even further by actually implementing a new hybrid algorithm that takes into consideration all four models that we have compared in this paper. This is because from the results that we derived from our study, it's evident that none of the models is perfect and each model has both merits and demerits under a given situation. Hence we would like to implement a hybrid model that takes into consideration the type of network it is working on and based on that the hybrid algorithm will select the relevant model. This may ensure enhanced performance and result in a more optimal and efficient model for gateway selection . Furthermore, we learned previously from our research that there is no 'standard' protocol for a general purpose gateway selection in IoT. Hence in future we hope to work on this hybrid algorithm that can be used as a 'standard' protocol for all types of gateway selection in IoT.

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Appendix

Datasets

1. The datasets collected for Taxi-Sharing model
https://drive.google.com/drive/folders/1J_Vfj0Zx7W0WUHp1U9MGWiDNUWHz82h5?usp=sharing

2. The datasets collected for GTGWS model
https://drive.google.com/drive/folders/1SEPr7ZY1Lu94Bs9GAal7u9A8K0pPuVtv?usp=sharing

3. The datasets collected for FWM model
https://drive.google.com/drive/folders/1uCRtdSzLz-Tjwarn8KwXQjZ46VYKMa8a?usp=sharing

4. The datasets collected for ERGTS model
https://drive.google.com/drive/folders/1J_Vfj0Zx7W0WUHp1U9MGWiDNUWHz82h5?usp=sharing

Code

1. Taxi-Sharing model
https://drive.google.com/drive/folders/1GIpDLfqXgmu8mRzoCF6VtAPIeRR_0wLk?usp=sharing

2. GTGWS and FWM model
https://drive.google.com/drive/folders/1HvyNs2DulZtqZmUjmM-KKGY_FvpC6ayC?usp=sharing

3. ERGTS model
https://drive.google.com/drive/folders/1Zokk0rRRNA1SWnn0iYdON2v0kafF9O4E?usp=sharing