ANALYSIS OF FREQUENCY HOPPING SCHEMES

A Project Report

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NEEHARIKA C V

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THESIS CERTIFICATE

This is to certify that the thesis titled **ANALYSIS OF FREQUENCY HOPPING SCHEMES**, submitted by **NEEHARIKA C V**, to the Indian Institute of Technology, Madras, for the award of the degree of **Bachelor of Technology & Master of Technology**, is a bonafide record of the research work done by her under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Prof. K. Giridhar
Research Guide
Professor
Dept. of Electrical Engineering
IIT-Madras, 600 036

Place: Chennai

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ABSTRACT

A single-hop frequency hopping mobile ad hoc network (MANET) is considered. The total available bandwidth is divided into M orthogonal channels. When the number of available orthogonal channels (M) is greater than the number of users in the MANET, Orthogonal FH (O-FH) improves throughput over the Uncoordinated FH (U-FH) by allowing collision-free transmissions. However, when the number of users exceeds the number of available orthogonal channels, the O-FH scheme cause deterministic collisions at some users having the same hopping sequences.

The Collision-Balancing FH scheme is based on O-FH. Furthermore, it introduces fairness in interference for all users when the number of users exceeds the number of orthogonal channels (M). However, collisions are not evenly distributed among channels, resulting in unfair channel usage. This problem is addressed in this work, by modifying the CB-FH scheme to ensure that all users collide with each other in all frequency channels in a hopping sequence. This resulted in a balanced channel utilisation for collisions. The outage probability, on the other hand, has not changed.

In this work, Collision Free Frequency Hopping (CF-FH) Scheme is proposed to eliminate the collisions among the users when the number of users in the MANET exceeds the number of available orthogonal channels. In every hopping sequence, this scheme allows fair usage of orthogonal frequency channels by the users. Since there are no collisions, the outage probability is always zero. It is also found that the CF-FH scheme gives higher throughput when compared to the CB-FH scheme.

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ABBREVIATIONS

FH	Frequency Hopping
FHSS	Frequency Hopping Spread Spectrum
U-FH	Uncoordinated Frequency Hopping
O-FH	Orthogonal Frequency Hopping
CB-FH	Collision Balancing Frequency Hopping
CF-FH	Collision Free Frequency Hopping
MANET	Mobile ad hoc network
OP	Outage Probability
WPAN	Wireless Personal Area Network
FFH	Fast Frequency Hooping
OFDM	Orthogonal Frequency Division Multiplexing
VA	Vehicular A
IOA	Indoor Office A

CHAPTER 1

INTRODUCTION

MANETs are mobile wireless networks which are adaptive and self organizing without any fixed infrastructure. Frequency hopping techniques are used to avoid interference in MANETs. Frequency hopping spread spectrum is generally known to avoid the narrow band interference, jamming by allowing the signals to rapidly switch among various frequency channels. In FHSS, the entire bandwidth W is divided into M orthogonal frequency channels with equal bandwidth of $\frac{W}{M}$.

A few Frequency Hopping schemes include uncoordinated FH, orthogonal FH, and collision balancing FH (1). The hopping sequences of the users in U-FH are not synchronized in time, resulting in significant interference. The hopping sequences in O-FH are time-synchronized, resulting in the minimum interference. In the case of O-FH, there will be no collisions if there are enough orthogonal channels. However, once the number of users exceeds the number of available orthogonal channels, deterministic collisions between users who utilize the same hopping sequences will occur. This creates unfair interference at some users.The CB-FH scheme resolves the unfair interference situation at the nodes. CB-FH, like O-FH, minimizes the number of collisions in each hop. Furthermore, by distributing the total possible collisions over time, it generates a fair interference situation for all users. **Collision Free Frequency Hopping** Scheme is proposed to totally eliminate collisions when the number of users exceeds the number of available orthogonal channels.

The performance of these frequency hopping schemes is compared in this work using metrics such as Hit Probability, Outage Probability, Spectral Efficiency, and System Throughput. The CF-FH scheme's outage probability is always zero, which is better than the previous FH schemes. Despite a trade-off in spectral efficiency, the CF-FH scheme has a higher system throughput than the CB-FH scheme.

CHAPTER 2

LITERATURE SURVEY

2.1 Frequency Hopping Schemes

Collision Balancing Frequency hopping scheme is introduced in (1) and its performance is compared with the following reference frequency hopping schemes:

1. Uncoordinated Frequency Hopping
2. Orthogonal Frequency Hopping

It is built on Orthogonal frequency hopping scheme. Furthermore, the Collision Balancing FH scheme ensures that all nodes in an ad hoc network experience same number of collisions in 1 hopping sequence. A single hop MANET is considered, which consists of N node pairs that are uniformly distributed on a disc. Let $\{X_1$,X_2,...,X_{N-1},$X_N\}$ represents the set of node pairs. The total available bandwidth is divided into a set of M orthogonal channels. $\{f_1$,f_2,f_3,...,f_{M-1},$f_M\}$ are the set of centre frequencies for the M orthogonal channels.

2.1.1 Uncoordinated Frequency Hopping Scheme

There is no synchronization of hopping sequences in U-FH scheme. In any hop, each node pair can choose any orthogonal channel with a uniform probability of $\frac{1}{M}$. As a result, the users may encounter any number of collisions during a hop.

Example 1: When $N \leq M$

Consider a single hop MANET with $N = 4$ and $M = 5$ orthogonal channels. Using the Uncoordinated Frequency Hopping Scheme, the matrix below depicts one possible assignment of orthogonal channels to the node pairs in 5 hops. Each row of the matrix corresponds to a node pair and each column corresponds to a single hop. Each entry of the matrix has the centre frequency of the orthogonal channel used by the corresponding node pair in that particular hop. In the first hop, X_1, X_2, X_4 use the same channel with center frequency f_1. So, they collide with one another and result in $\binom{3}{2} = 3$ collisions. In the 5th hop, all node pairs use the same orthogonal channel with centre frequency f_4 and may result in $\binom{4}{2} = 6$ collisions.

$$\begin{matrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{matrix} \begin{bmatrix} f_1 & f_2 & f_3 & f_5 & f_4 \\ f_1 & f_3 & f_1 & f_5 & f_4 \\ f_4 & f_4 & f_3 & f_5 & f_4 \\ f_1 & f_5 & f_2 & f_1 & f_4 \end{bmatrix}$$

Example 2: When $N > M$

Consider a single hop MANET with $N = 6$ and $M = 3$ orthogonal channels. Using the Uncoordinated Frequency Hopping Scheme, the matrix below depicts one possible assignment of orthogonal channels to the node pairs in 3 hops. In the first hop, X_2, X_4, X_5 use the same channel with center frequency f_3, resulting in 3 collisions among these nodes, whereas X_3, X_6 use the same channel with center frequency f_2 resulting in a collision.

$$\begin{matrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \end{matrix} \begin{bmatrix} f_1 & f_2 & f_3 \\ f_3 & f_1 & f_2 \\ f_2 & f_2 & f_1 \\ f_3 & f_2 & f_3 \\ f_3 & f_1 & f_1 \\ f_2 & f_3 & f_1 \end{bmatrix}$$

2.1.2 Orthogonal Frequency Hopping Scheme

When the number of node pairs is fewer than or equal to the number of available orthogonal channels ($N \leq M$), there will be no collisions in orthogonal frequency hopping. However, when the number of node pairs in the ad hoc network exceeds the number of orthogonal channels ($N > M$), the node pairs having unique hopping sequence experience no collisions, whereas the node pairs re-using the hopping sequence will always encounter deterministic collisions. For Orthogonal frequency hopping, the hopping sequence length is M, and the sequence repeats in subsequent hops.

Example 1: When $N \leq M$

Consider a single hop MANET with N = 4 and M = 5 orthogonal channels. The matrix below depicts one possible assignment of orthogonal channels to the node pairs using orthogonal frequency hopping. Each row of the the matrix represents the node pairs and each column represents a hop. Each entry of the matrix is the center frequency of the orthogonal channel used by that node for that hop. The first M hops correspond to one hopping sequence. We can see that none of the nodes collide in any hop when $N \leq M$.

$$\begin{matrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{matrix} \begin{bmatrix} f_1 & f_2 & f_3 & f_4 & f_5 \\ f_2 & f_3 & f_4 & f_5 & f_1 \\ f_3 & f_4 & f_5 & f_1 & f_2 \\ f_4 & f_5 & f_1 & f_2 & f_3 \end{bmatrix}$$

Example 2: When $N > M$

Consider a single hop MANET with N = 6 and M = 4 orthogonal channels. The matrix below depicts one possible assignment of orthogonal channels to the node pairs using orthogonal frequency hopping. Since $N > M$ few node pairs use a unique hopping sequence whereas few other node pairs will have to re-use a hopping sequence which is already used by other node pairs. The length of the hopping sequence is equal to M. X_1, X_3 have unique hopping sequences, whereas X_2, X_5 have the same hopping sequence and X_4, X_6 have the same hopping sequence. This results in deterministic collisions between X_2, X_5 and X_4, X_6 in all the hops.

$$\begin{matrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \end{matrix} \begin{bmatrix} f_1 & f_2 & f_3 & f_4 \\ f_2 & f_3 & f_4 & f_1 \\ f_3 & f_4 & f_1 & f_2 \\ f_4 & f_1 & f_2 & f_3 \\ f_2 & f_3 & f_4 & f_1 \\ f_4 & f_1 & f_2 & f_3 \end{bmatrix}$$

2.1.3 Collision Balancing Frequency Hopping Scheme

The Collision Balancing Frequency hopping scheme is built based on the Orthogonal Frequency hopping scheme. It is same as the Orthogonal Frequency Hopping scheme when $N < M$. So there will not be any collisions when $N < M$. When N exceeds M, then there will be collisions among the node pairs.

Collision Balancing Frequency Hopping scheme proposes an algorithm to generate the hopping sequence which

1. minimizes the total number of collisions
2. achieves fair interference at the nodes

The total number of possible collisions is $\frac{N(N-1)}{2}$. The CB-FH scheme allows the minimum number of collisions per frequency hop, which is $N - M$, for $N > M$. As a result, the length of the hopping sequence L is chosen so that the total number of possible collisions is evenly spread across time, resulting in fair interference at all nodes. The sequence length is given by $\frac{N(N-1)}{2(N-M)}$, $N > M$. Synchronous FHSS is assumed here, which means all nodes will hop synchronously into the set of frequency channels in every hop period, .

Example 1: When $N \leq M$

Consider a single hop MANET with $N = 4$ and $M = 5$ orthogonal channels. Since $N < M$, CB-FH is same as O-FH.

Example 2: When $N > M$

Consider a single hop MANET with $N = 7$ and $M = 4$ orthogonal channels.The matrix below depicts one possible assignment of orthogonal channels to the node pairs using Collision Balancing frequency hopping. The total number of possible collisions is $\frac{7(7-1)}{2} = 21$. The hopping sequence length L = $\frac{7(7-1)}{2(7-4)} = 7$ and there will be $N - M = 3$ collisions in every hop to distribute the total number of collisions across 7 hops.

$$
\begin{array}{c}
X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \\ X_7
\end{array}
\begin{bmatrix}
f_1 & f_3 & f_3 & f_4 & f_4 & f_4 & f_3 \\
f_3 & f_4 & f_2 & f_2 & f_3 & f_2 & f_3 \\
f_4 & f_1 & f_3 & f_2 & f_1 & f_1 & f_4 \\
f_2 & f_3 & f_1 & f_3 & f_2 & f_2 & f_4 \\
f_1 & f_2 & f_2 & f_1 & f_2 & f_1 & f_2 \\
f_4 & f_4 & f_1 & f_1 & f_4 & f_3 & f_1 \\
f_2 & f_1 & f_4 & f_4 & f_3 & f_3 & f_2
\end{bmatrix}
$$

2.2 Related work

In (5), Orthogonal Hop set partitioning scheme is proposed to reduce collisions among the bluetooth piconets using orthogonal partitioning of the hopping set. Frequency Rolling technique is introduced in (6), Dynamic Adaptive Frequency Hopping is dicussed in (7), to cooperatively avoid the self-interference among the collocated WPANs.

2.3 FFH/OFDM

The FFH/OFDM concept is based on integrating orthogonal frequency division multiplexing (OFDM) and Fast Frequency hopping (FFH) concepts. Although OFDM offers a high data throughput, it lacks frequency diversity when applied to mobile radio with time-varying multipath propagation. So, FFH/OFDM concept is introduced in (2), (3) to exploit frequency diversity by spreading data over several frequency subcarriers.

CHAPTER 3

Modified Collision Balancing Frequency Hopping Scheme

3.1 Introduction

Fairness is achieved in the Collision Balancing Frequency Hopping Scheme by distributing collisions to all users in a single hopping sequence (L hops) when $N > M$. However, it is unclear which channels should be used for these collisions. As a result, there is no fairness in channel usage for collisions. By distributing collisions across all channels over time, we can achieve fairness in channel usage for collisions. Any user must collide with all other users in all available frequency channels, hence the hopping sequence length should be ML.

Example 1: Consider a single hop MANET with $N = 5$ and $M = 3$ orthogonal channels ($N > M$). The length of the hopping sequence according to CB-FH scheme is $L = \frac{5(5-1)}{2(5-3)} = 5$. For $N = 5, M = 3$, one possible hopping sequence obtained using the CB-FH scheme is shown below. In one hopping sequence of length 5, we see 2 collisions in channel f_1, 5 collisions in channel f_2, and 3 collisions in channel f_3. As a result, collisions may be more frequent in some channels than others.

$$\begin{matrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{matrix} \begin{bmatrix} f_3 & f_2 & f_2 & f_2 & f_3 \\ f_2 & f_3 & f_1 & f_1 & f_3 \\ f_1 & f_2 & f_1 & f_3 & f_1 \\ f_1 & f_3 & f_3 & f_2 & f_2 \\ f_2 & f_1 & f_2 & f_3 & f_2 \end{bmatrix}$$

So we increase the length of the hopping sequence to $ML = 15$ to make collisions more evenly distributed among the channels. The hopping sequence is shown below.

$$
\begin{array}{c}
X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5
\end{array}
\begin{bmatrix}
f_3 & f_2 & f_2 & f_2 & f_3 & f_1 & f_3 & f_3 & f_3 & f_1 & f_2 & f_1 & f_1 & f_1 & f_2 \\
f_2 & f_3 & f_1 & f_1 & f_3 & f_3 & f_1 & f_2 & f_2 & f_1 & f_1 & f_2 & f_3 & f_3 & f_2 \\
f_1 & f_2 & f_1 & f_3 & f_1 & f_2 & f_3 & f_2 & f_1 & f_2 & f_3 & f_1 & f_3 & f_2 & f_3 \\
f_1 & f_3 & f_3 & f_2 & f_2 & f_2 & f_1 & f_1 & f_3 & f_3 & f_3 & f_2 & f_2 & f_1 & f_1 \\
f_2 & f_1 & f_2 & f_3 & f_2 & f_3 & f_2 & f_3 & f_1 & f_3 & f_1 & f_3 & f_1 & f_2 & f_1
\end{bmatrix}
$$

In one hopping sequence of length 15, we see 10 collisions in channel f_1, 10 collisions in channel f_2, and 10 collisions in channel f_3. As a result, collisions are evenly distributed in all the frequency channels.

3.2 Algorithm

The algorithm in (1) is used to generate a hopping sequence for CB-FH scheme. This algorithm is extended to generate the hopping sequence of length ML with fair usage of channels for collisions. Let s_i be the hopping sequence used by X_i generated using the CB-FH scheme (1). $s_i(k)$ is the frequency channel for X_i in k_{th} hop, where $k \in \{1, 2, ..., L\}$. Let e_i be the hopping sequence for X_i generated using the modified CB-FH scheme. $e_i(k)$ is the frequency channel used by X_i in k_{th} hop, where $k \in \{1, 2, ..., ML\}$.

Algorithm 1 Generate Hopping sequence of length ML

for $k = 1$ to L **do**
  for $i = 1$ to N **do**
    $e_i(k) \leftarrow s_i(k)$
  end for
end for
for $j = 1$ to $M - 1$ **do**
  for $i = 1$ to N **do**
    for $k = 1$ to L **do**
      $e_i(jL + k) \leftarrow \big[e_i\big((j-1)L + k\big) \pmod M + 1\big]$
    end for
  end for
end for

CHAPTER 4

Collision Free Frequency Hopping scheme

4.1 Introduction

Collision Free Frequency Hopping scheme aims to eliminate collisions completely and achieve fair usage of all available orthogonal channels when the number of users exceeds the number of available orthogonal channels ($N > M$). Each of the M orthogonal channels is used only once every hop. As a result, only M out of N users transmit and there will be no collisions in any hop. The length of the hopping sequence is set to N, which ensures that each orthogonal channel is used by each user once per hopping sequence.There will be no collisions because only M users are allowed to transmit in each hop. Since there is no interference in any hop, the outage probability is always zero. However, the CF-FH scheme has a higher system throughput than CB-FH Scheme.

Example 1: Consider a single-hop MANET with $N = 5$ and $M = 3$ orthogonal channels ($N > M$). The length of the hopping sequence is $N = 5$. The zero entries in the below matrix indicate that the corresponding users are not transmitting in that hop. We see that all the 3 orthogonal channels are used only once in any hop. As a result, there are no collisions.

$$\begin{matrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{matrix} \begin{bmatrix} f_1 & f_2 & f_3 & 0 & 0 \\ 0 & f_1 & f_2 & f_3 & 0 \\ 0 & 0 & f_1 & f_2 & f_3 \\ f_3 & 0 & 0 & f_1 & f_2 \\ f_2 & f_3 & 0 & 0 & f_1 \end{bmatrix}$$

Example 2: Consider a single-hop MANET with $N = 7$ and $M = 5$ orthogonal channels ($N > M$). The length of the hopping sequence is $N = 7$. The zero entries in the below matrix indicate that the corresponding users are not transmitting in that hop. We see that all the 5 orthogonal channels are used only once in any hop. As a result, there are no collisions.

$$\begin{array}{c} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \\ X_7 \end{array} \begin{bmatrix} f_1 & f_2 & f_3 & f_4 & f_5 & 0 & 0 \\ 0 & f_1 & f_2 & f_3 & f_4 & f_5 & 0 \\ 0 & 0 & f_1 & f_2 & f_3 & f_4 & f_5 \\ f_5 & 0 & 0 & f_1 & f_2 & f_3 & f_4 \\ f_4 & f_5 & 0 & 0 & f_1 & f_2 & f_3 \\ f_3 & f_4 & f_5 & 0 & 0 & f_1 & f_2 \\ f_2 & f_3 & f_4 & f_5 & 0 & 0 & f_1 \end{bmatrix}$$

The outage probability is zero in both of the examples described above since none of the users collide in any frequency hop resulting in zero interference.

4.2 Algorithm

The following algorithm can be used to design hopping sequence for CF-FH. Let s_i be the hopping sequence for X_i generated using the CF-FH scheme. $s_i(k)$ is the frequency channel for X_i in k_{th} hop, where $k \in \{1, 2, ..., N\}$. Initialize the hopping sequence of all users to zeroes. Then, follow the below algorithm to generate the hopping sequence set.

Algorithm 2 Generate Hopping sequence of length N using CF-FH

```
for i = 1 to N do
    for j = 0 to M − 1 do
        hop ← [(i + j) (mod N)]
        if hop is 0 then
            hop ← N
        end if
        s_i(hop) ← (j + 1)
    end for
end for
```

CHAPTER 5

EXPERIMENTAL RESULTS

5.1 Bluetooth Experiment

To avoid packet collisions, Bluetooth uses a type of Frequency hopping Spread spectrum termed **Adaptive frequency hopping**. It operates in the 2.4 GHz ISM band. It employs Time Division Duplexing (TDD), with each time slot lasting 625 mus. After each time slot, it hops to a different frequency at a rate of 1600 hops/s.

A Bluetooth piconet is a mobile ad hoc network with a master and up to seven active slaves. The presence of Co-channel interference among the piconets degrades Bluetooth performance. According to the Bluetooth Architecture, packet transmission is considered to be successful when the sender receives an acknowledgement from the receiver.If it is lost, the sender must retransmit the packet.

An experiment has been performed to analyse the performance of two un-synchronised Bluetooth links. Two pairs of mobile devices (A,B) and (C,D) are used for the experiment. The devices in each pair are connected via Bluetooth. (A,B) and (C,D) form two un-synchronised links. Different files of varying sizes are transferred between the devices in each of the pairs in two different scenarios:

1. When both device pairs (A,B) and (C,D) are placed on the same table,
2. When both (A,B) and (C,D) pairs are in different rooms.

The data rates are relatively lower in the first scenario when both pairs of devices are placed on the same table, as shown in Table 5.1. Since the links are un-synchronized, there is higher potential for interference when both pairs of devices are placed on the same table. The interference present can be due to the hopping into same frequency locations at the same time slot which leads to data loss and hence there will be retransmission of packets in the first scenario. By using synchronous hopping, data rates can be improved.So synchronous hopping is assumed for O-FH, CB-FH and CF-FH to get better data rates.

Table 5.1: Observed Data rates denoted in Mbps, Size of the file denoted in MB

S.No	Devices	Size of the file	Data rate (Same Table)	Data rate (Different Room
1	(A,B)	26.5	0.1586	0.2154
	(C,D)		0.1587	0.1677
2	(A,B)	19.18	0.1669	0.2131
	(C,D)		0.1598	0.1625
3	(A,B)	12.76	0.1301	0.1533
	(C,D)		0.0621	0.1521

5.2 Performance Analysis of Frequency Hopping Schemes

5.2.1 Comparison of hit probabilities

The hit probability is defined as the probability of at least one collision experienced by a node pair in a frequency hop. When $N > M$, each node pair in Orthogonal frequency hopping, Collision Balancing Frequency hopping schemes experiences only one collision in any frequency hop, so the hit probability is equal to probability of one collision. Each node pair in Uncoordinated Frequency hopping scheme experiences one or more collisions in any frequency hop.

1. **Uncoordinated FH:** The hit probability is

$$p_h^U = 1 - (1 - \tfrac{1}{M})^{N-1}$$

2. **Orthogonal FH:** The hit probability is

$$p_h^O = \begin{cases} 1, & \text{if hopping sequence is re-used} \\ 0, & \text{if hopping sequence is unique} \end{cases} \tag{5.1}$$

3. **Collision Balancing FH:** The hit probability is

$$p_h^{CB} = \begin{cases} 0, & 1 \leq \text{N} < \text{M} \\ 2(1 - \frac{M}{N}), & \text{M} \leq \text{N} < 2\text{M} \end{cases} \tag{5.2}$$

Figure 5.1 depicts these hit probabilities. Over a wide range of $\frac{N}{M}$ values, it can be seen that Collision Balancing FH has a lower hit probability than Uncoordinated FH and Orthogonal FH schemes. Collision Balancing FH scheme has a higher hit probability than Uncoordinated FH system after a specific value of $\frac{N}{M} \approx 1.68$. However, this does not imply that the U-FH outperforms the CB-FH, because hit probability ignores the

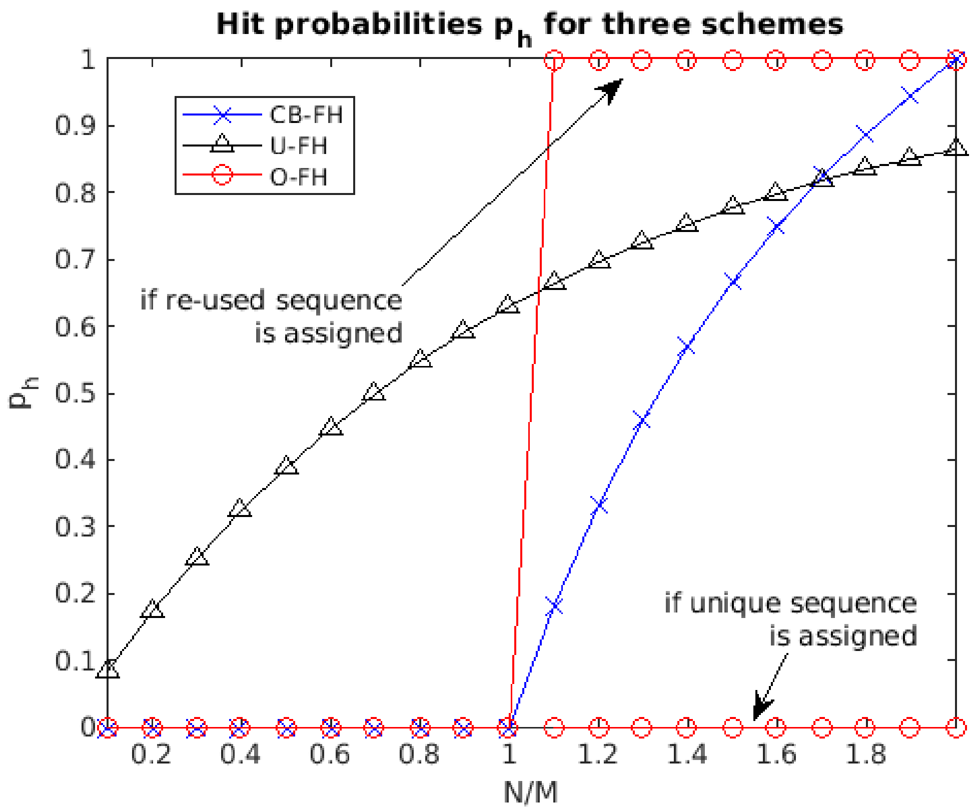

Figure 5.1: Hit Probabilities vs. $\frac{N}{M}$

number of users colliding with a given user in the event of at least one collision. As a result, hit probability cannot be used as the sole metric for evaluating the performance of these schemes. So we compare the Outage probabilities of these FH schemes.

5.2.2 Comparison of Outage Probability

Comparison of Outage Probability for CB-FH, O-FH, CF-FH

Figure 5.2 compares the performance of these FH schemes by plotting the outage probability against $\frac{N}{M}$. Every node transmits independently with a probability of λ. When $N \leq M$, the outage probability for Orthogonal and Collision Balancing FH systems is zero. The outage probability of the CB-FH scheme increases as $\frac{N}{M}$ grows from 1 to 2. However, its outage probability is lower than that of the O-FH and U-FH schemes for $\lambda = 0.5, 1$.

This demonstrates that the CB-FH scheme reduces the total number of collisions while ensuring fair interference at all nodes. The Outage probability plot in Figure 5.2

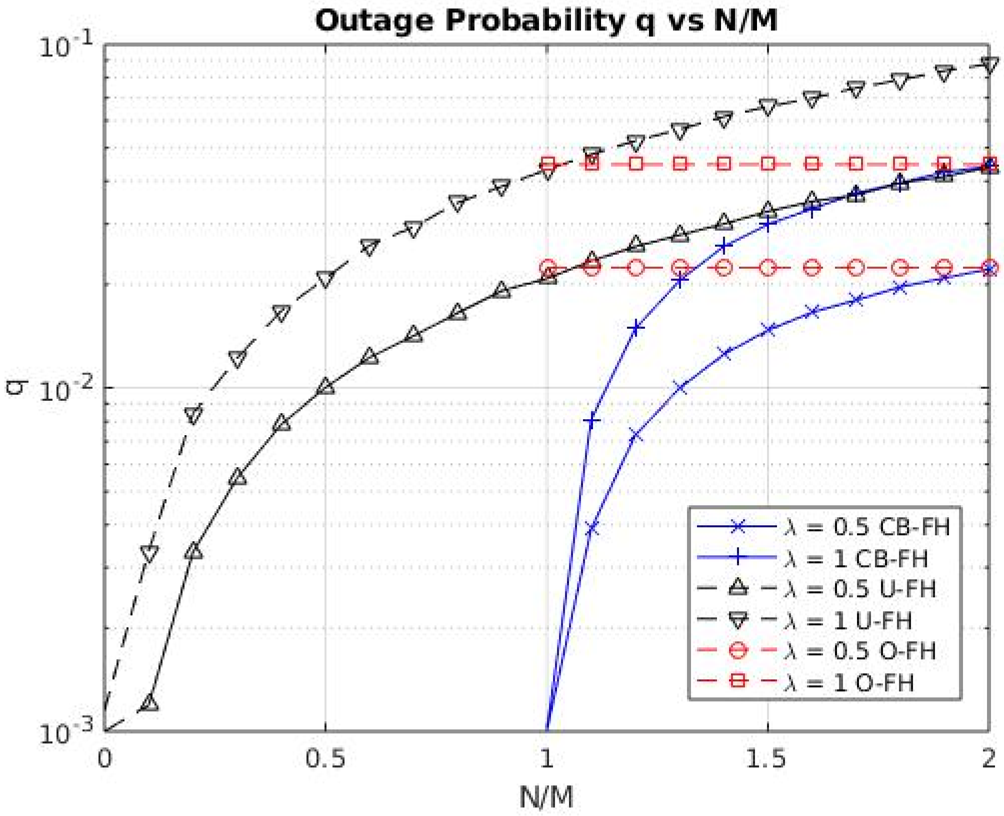

Figure 5.2: OP vs. $\frac{N}{M}$, The simulation parameters are: (radius of disk) $D = 100$, $x_1 = (D/2, 0)$, $\beta = 2$, $S(x_1)$ = -50 dB, ϵ= 1, $\alpha = 4$.

is reproduced using the following Interference expression in (1).

$$I(x_1) = \sum_{i=2}^{N} \frac{B_i}{\epsilon + \|X_i - x_1\|^{\alpha}}, \; where \;\; B_i = \begin{cases} 1, & \text{if } X_i \text{ is Tx and hits node } x_1 \\ 0, & \text{else} \end{cases} \tag{5.3}$$

x_1 is in outage if the signal-to-interference ratio $\frac{S(x1)}{I(x1)}$ is below a threshold β.

Outage probability with varying lambda

In Figure 5.3, the Outage probability is plotted against $\frac{N}{M}$ for $\lambda = 0.25, 0.5, 0.75, 1$ for the CB-FH scheme. The trend of Outage probability plot is same for any λ. At any value of $\frac{N}{M}$, we can see that the outage probability increases with increase in λ, due to the increase in the number of transmitters.

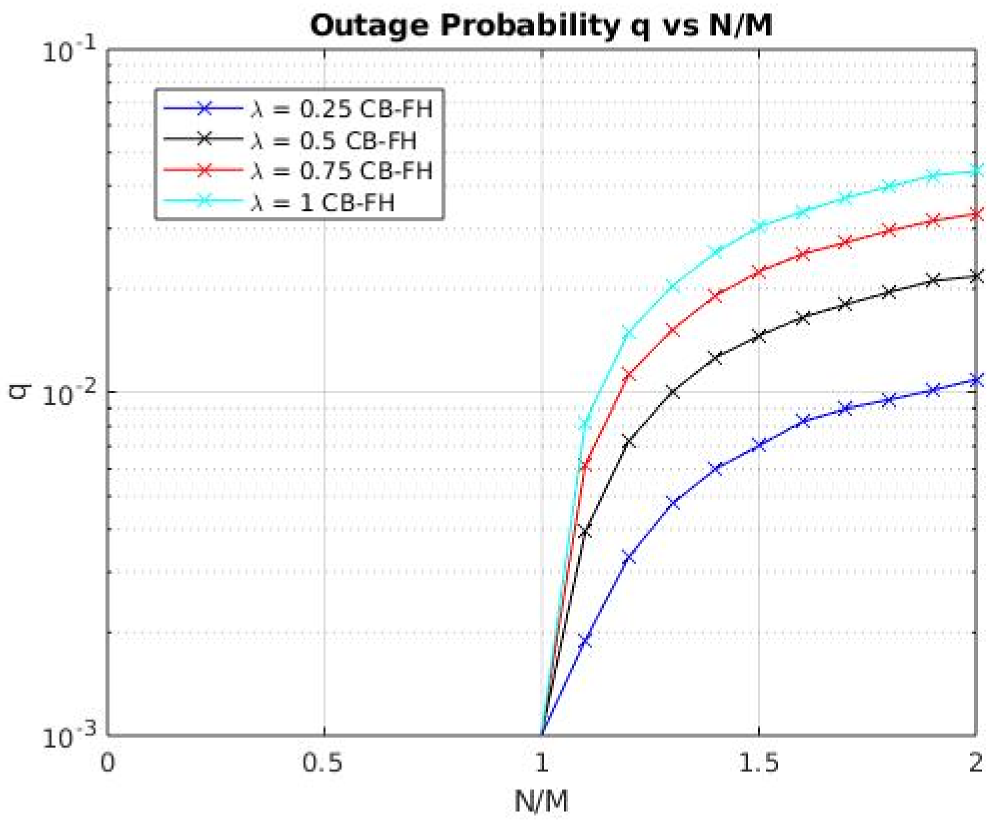

Figure 5.3: Outage Probability for Collision Balancing FH scheme with varying λ

Comparison of Outage Probability for CB-FH, Modified CB-FH

The outage probability of the CB-FH scheme is compared to that of the Modified CB-FH scheme with ML as hopping sequence length. The outage probabilities of both schemes are the same for $\lambda = 0.5, 1$, as shown in Figure 5.4

5.2.3 Comparison of Spectral Efficiency

In Figure 5.5, the Spectral Efficiency of CF-FH scheme is compared to the spectral efficiency of CB-FH scheme for $\lambda = 0.25, 0.5, 0.75, 1, \frac{M}{N}$. The spectral efficiency of CF-FH scheme remains constant as $\frac{N}{M}$ increases and it is identical to the spectral efficiency of the CB-FH scheme when λ= $\frac{M}{N}$. However, for lower λs, the spectral efficiency of the CF-FH scheme is higher than that of the CB-FH scheme, but lower than that of the CB-FH scheme for higher λs.

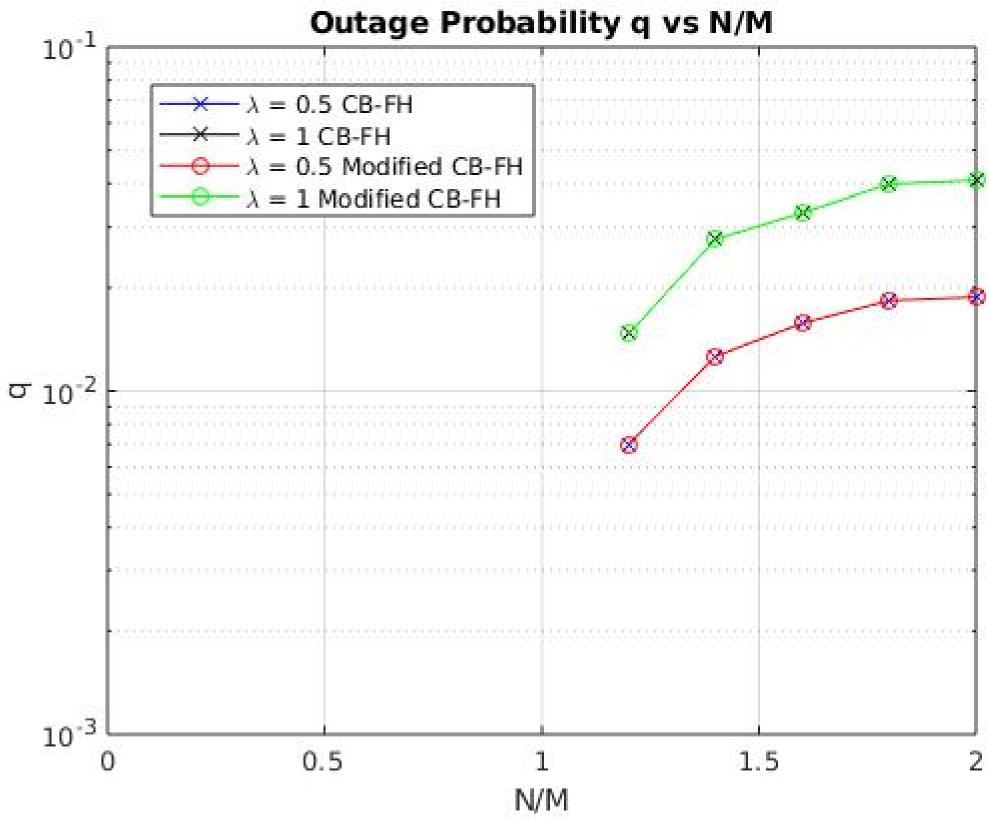

Figure 5.4: Outage Probability comparison for CB-FH, Modified CB-FH

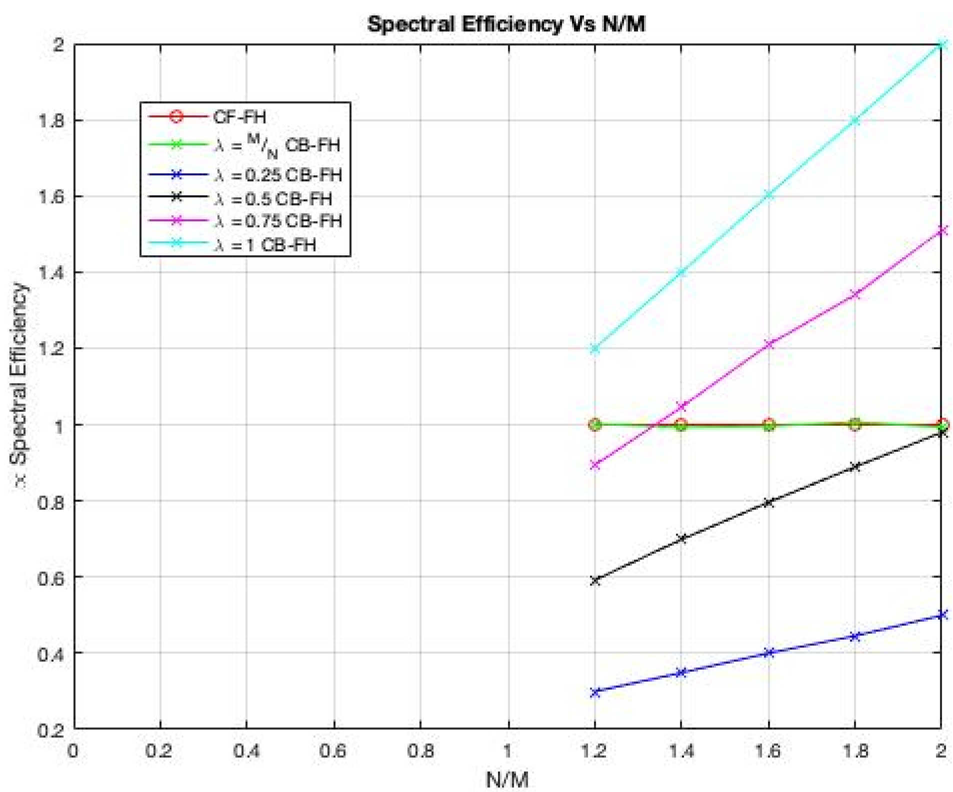

Figure 5.5: Spectral Efficiency comparison for Collision Balancing, Collision Free FH schemes λ

5.2.4 Comparison of System Throughput

Throughput can be calculated as follows:

$$Throughput = Spectral\ Efficiency(1 - BLER) \tag{5.4}$$

$$Throughput = [M(\frac{y * p}{(\frac{W}{M})})]\lambda(1 - BLER) = k * [y\lambda(1 - BLER)] \tag{5.5}$$

$$Throughput \propto [y\lambda(1 - BLER)] \tag{5.6}$$

where $BLER$ is Block Error Rate, $k = \frac{M^2 p}{W}$, data rate per packet is $p\ bits/s$. y is the average number of times data is transmitted through a particular orthogonal channel (let f_1) in a single hop. W is the total available bandwidth. $\frac{W}{M}$ is the bandwidth of single orthogonal channel. In CB-FH scheme, all nodes independently decide whether to transmit or not with probability λ. In CF-FH scheme, λ=$\frac{M}{N}$ is the fraction of active transmitters in any hop.

Let $G = y\lambda(1-BLER)$. Throughput is proportional to G. Table 5.2 shows (system throughput $\propto$) G values for the CB-FH scheme for λ = 0.25,0.5,0.75,1,$\frac{M}{N}$ and CF-FH scheme. These G values are plotted in Figure 5.6 against $\frac{N}{M}$. For smaller values of λ, the throughput of the CB-FH scheme increases slowly with $\frac{N}{M}$, whereas for greater values of λ, the throughput decreases with $\frac{N}{M}$. For higher λ values in the CB-FH scheme, there will be more collisions as $\frac{N}{M}$ increases resulting in lower throughput. We see that the trend of the throughput curve for CF-FH scheme is similar to the throughput curve for CB-FH scheme when $\lambda = \frac{M}{N}$. However, we see that the CF-FH scheme's system throughput is higher than the CB-FH scheme's system throughput for any λ.

Table 5.2: (System throughput $\propto$) G values for CB-FH and CF-FH Schemes

$\frac{N}{M} \rightarrow$ / $\downarrow \lambda$	**1.2**	**1.4**	**1.6**	**1.8**	**2**
0.25	0.0687	0.0749	0.0812	0.0868	0.0935
0.5	0.2474	0.2503	0.2485	0.2493	0.2468
0.75	0.5037	0.4486	0.3944	0.3411	0.2795
1	0.7999	0.5996	0.4007	0.1999	0
$\frac{M}{N}$	0.6025	0.4224	0.3317	0.2820	0.2503
CF-FH	0.833	0.7143	0.625	0.5555	0.5

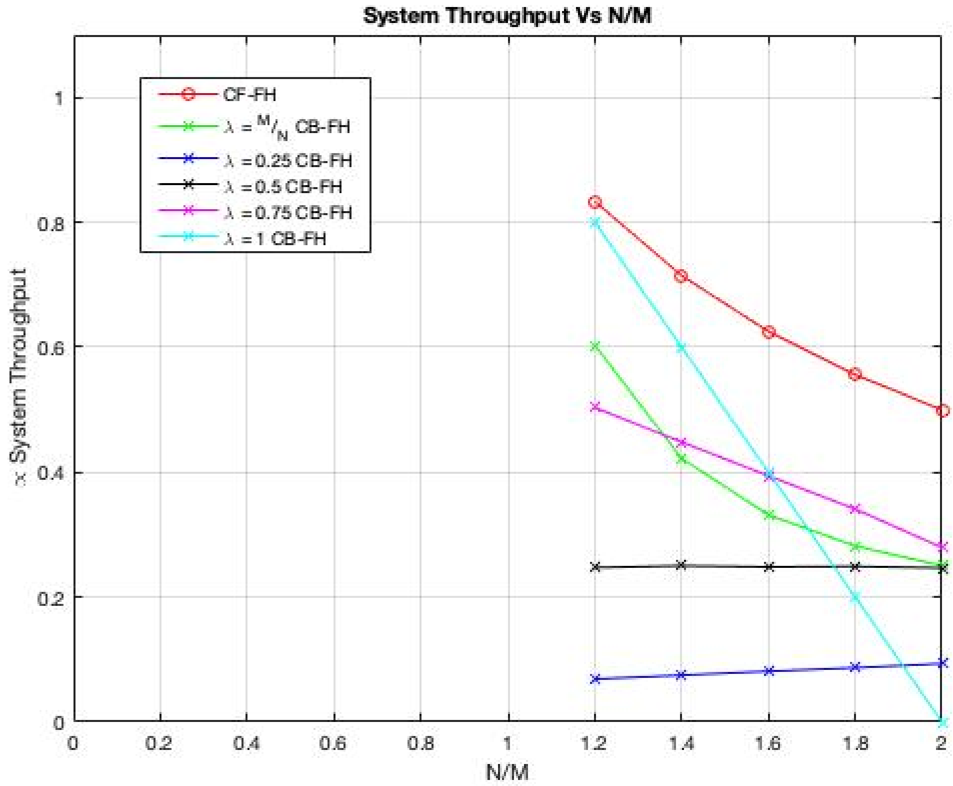

Figure 5.6: System Throughput comparison for Collision Balancing, Collision Free Frequency Hopping schemes, $M = 10$

5.3 Fast Frequency Hopping

Simulation results showing BER against SNR in (2) are reproduced for AWGN, Vehicular A and Indoor Office A channels for $M = 256$ sub-carriers. In Figure 5.7, we see that the performance of OFDM, FFH/OFDM are same for AWGN channel. In Figure 5.8, we see that FFH/OFDM has lower BER for higher values of SNR for both Vehicular A (VA) and Indoor Office A (IOA) channels. The performance gain of FFH/OFDM concept is larger in the VA channel than the IOA channel because of the lower delay spread in the IOA channel than the VA channel.

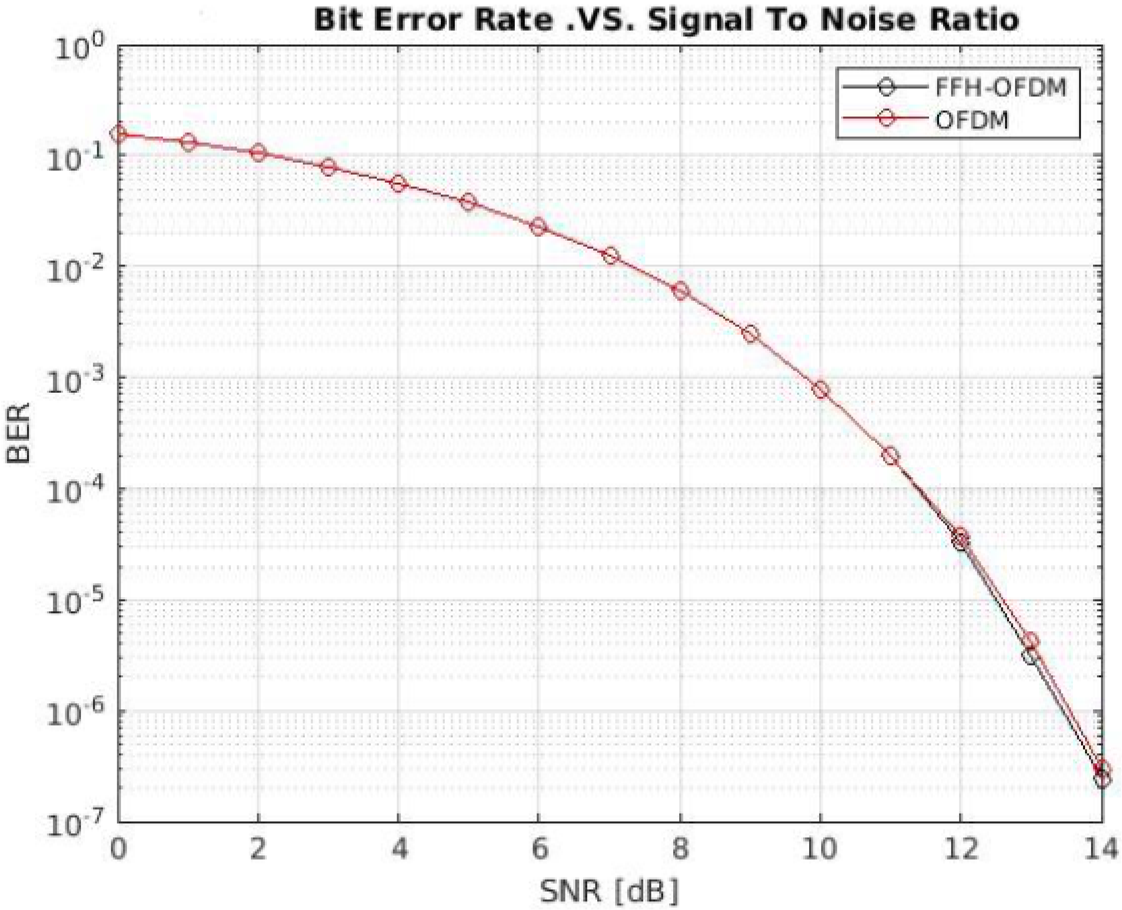

Figure 5.7: BER Vs SNR plot for AWGN channel, M=256 subcarriers

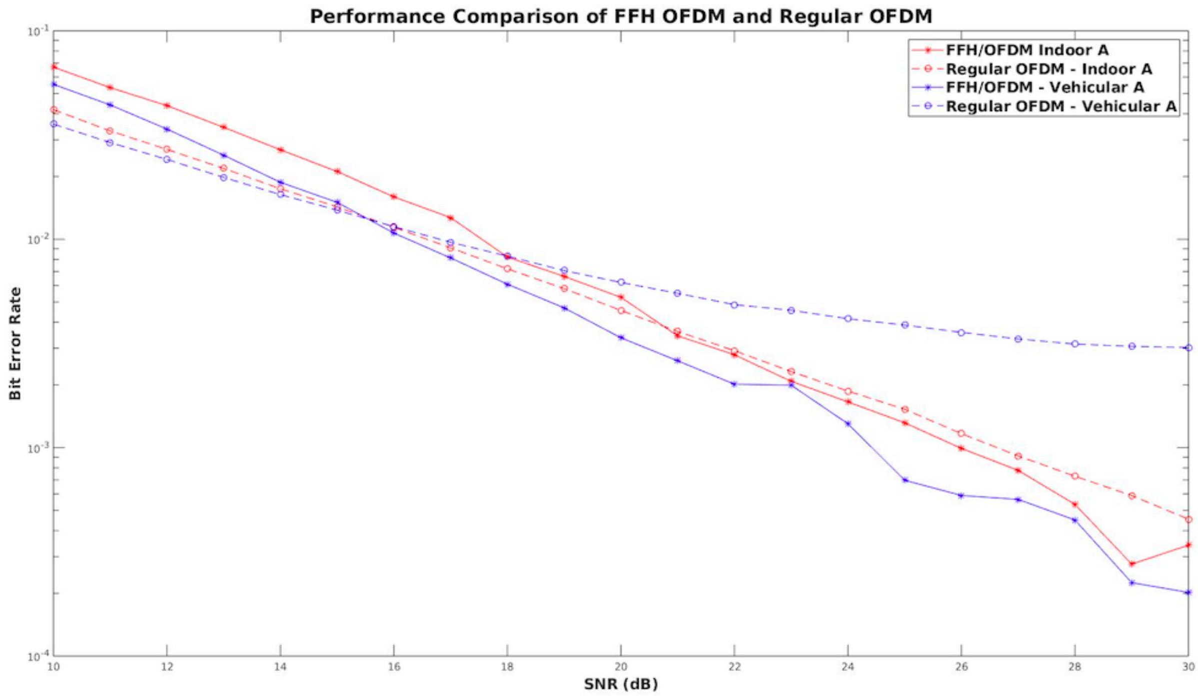

Figure 5.8: BER Vs SNR plot for Vehicular A, Indoor A channels, M=256 subcarriers

CHAPTER 6

CONCLUSION

The performance of CB-FH is found to be better when compared to U-FH and O-FH using metrics such as Hit probability and Outage Probability. CB-FH scheme is modified in this work to facilitate the fair usage of orthogonal channels for collisions. However, the outage probability has not improved. So, Collision Free Frequency Hopping (CF-FH) Scheme for MANETs is proposed in this work. The CF-FH scheme aims to establish a collision-free scenario leading to zero Outage Probability while also increasing throughput. The resulting hopping sequence set of length N

1. Eliminates all collisions resulting in zero Outage probability
2. Increases Throughput
3. Ensures fair usage of available orthogonal channels.

Using the throughput metric, the CF-FH scheme is shown to perform better than the CB-FH scheme.

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