Frequency Hopping Design and Interference Mitigation for Asynchronous Multi-user OFDM System

A Project Report

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THESIS CERTIFICATE

This is to certify that the thesis titled **Frequency Hopping Design and Interference Mitigation for Asynchronous Multi-user OFDM System**, submitted by **Pydi Muni Sreenivas**, to the Indian Institute of Technology Madras, Chennai for the award of the degree of **Bachelor of Technology**, is a bona fide record of the research work done by him 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.

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ABSTRACT

The project deals with designing a frequency hopping scheme for an interference limited, asynchronous, multi-user OFDM system. Several techniques for the mitigation of asynchronous interference in multi-user environment are discussed.

The need for fast acquisition and perfect orthogonality for the frequency hopping design leads to the use of short deterministic sequences rather than the usually employed pseudo-noise (PN) sequences. This report gives several frequency hopping designs involving deterministic sequences. Three schemes which cater to synchronous users, asynchronous users with single interferer, and finally, asynchronous users with multiple interferers are presented.

Asynchronicity among users in a multiple access system can occur at the level of hopping interval or at the level of symbol duration. For FH designs with deterministic sequences, the problem of asynchronous users is solved by repeating the data in the frequency domain. For the problem of asynchronicity at the symbol time level, a modified scheme involving repetition of data in the time domain is proposed. For this scheme, it is shown that by choosing a particular set of FFT windows to extract the data at the receiver, asynchronous interference can be mitigated as long as the delay spread is within the prescribed limits.

An OFDM system design that can support multiple users interfering asynchronously is derived, by employing the techniques of repetition of the data in time domain and frequency domain, to avoid interference. A deterministic frequency hopping scheme is used for the system. The system is highly flexible both in terms of the number of users supported and the data rates per user.

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ABBREVIATIONS

CDMA	Code Division Multiple Access
CP	Cyclic Prefix
DS	Delay Spread
DSSS	Direct Sequence Spread Spectrum
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
FH	Frequency Hopping
FHS	Frequency Hopping Sequence
FHSS	Frequency Hopping Spread Spectrum
HBR	High Bit Rate
ICI	Inter Carrier Interference
LB	Lower Band
LBR	Low Bit Rate
LFSR	Linear Feedback Shift Register
MBR	Medium Bit Rate
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PN	Pseudo Noise
TDMA	Time Division Multiple Access
UB	Upper Band

NOTATIONS

$H_{X,Y}$	Hamming cross-correlation between sequences X and Y
F	Frequency library
v	Length of frequency hopping sequence
M	Family size of the frequency hopping design
q	Size of the frequency library

CHAPTER 1

INTRODUCTION

1.1 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a multi-carrier data encoding technique in which a large number of closely spaced orthogonal sub-carrier signals are used to carry data on several parallel data streams. The block diagram for transmitter and receiver in an OFDM system is as shown in Figure 1.1.

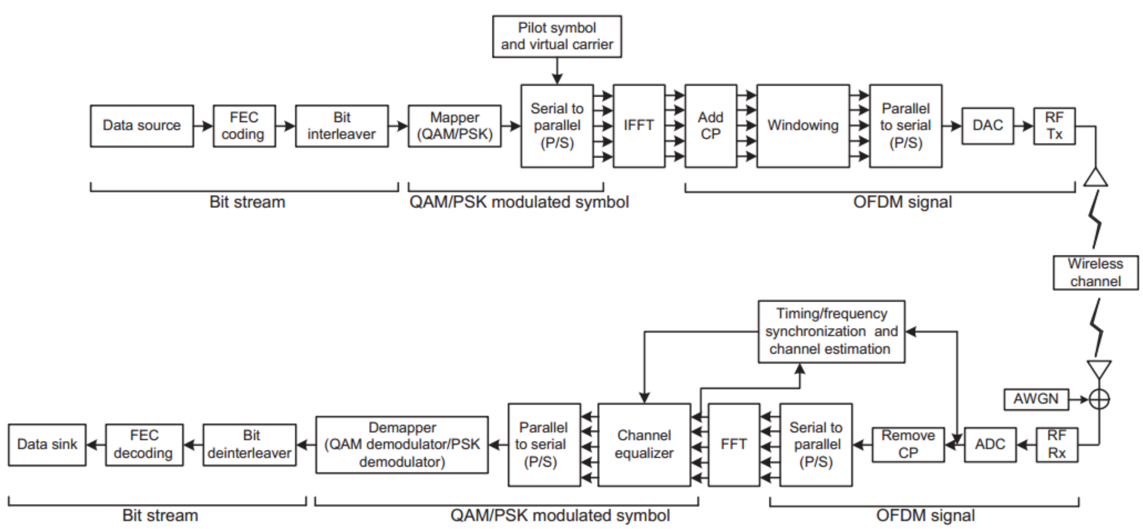

Figure 1.1: Block diagram for transmitter and receiver in an OFDM system

The primary advantage of OFDM over single-carrier schemes is its ability to cope with severe channel conditions (for example, narrowband interference and frequency-selective fading due to multipath) without complex equalization filters. Since the subcarriers are orthogonal, there is no cross-talk between them. So, unlike a conventional frequency division multiplexing (FDM) scheme, a separate filter for each sub-channel is not required, which greatly simplifies the design of both the transmitter and the receiver.

In general, OFDM is a transmission technique in which all subcarriers are used for transmitting the symbols of a single user. In other words, OFDM is not a multiple access technique by itself, but it can be combined with existing multiple access techniques such as TDMA (Time Division Multiple Access), FDMA (Frequency Division Multiple Access), and CDMA (Code Division Multiple Access) for a multi-user system. All subcarriers can be shared by multiple users in the forms of OFDM-TDMA, OFDMA (OFDM-FDMA), or MC-CDMA (OFDM-CDMA)

The OFDMA system assigns a subset of subcarriers (not all subcarriers in each OFDM symbol) to each user, where the number of subcarriers for a specific user can be adaptively varied in each frame. In other words, the subcarriers in each OFDM symbol are orthogonally divided among the multiple users. This resource allocation, i.e. the allocation of subcarriers to users, can be done in a random manner or in a deterministic manner, both of which have their own advantages and disadvantages.

In OFDMA, Frequency Hopping (FH) is a useful technique for allocating the subcarriers orthogonally among the users. In FH-OFDMA, the subcarriers of each OFDM symbol are assigned to different users according to hopping patterns or hopping sequences, which can be deterministic or pseudo-random.

1.2 Frequency Hopping Spread Spectrum (FHSS)

A spread spectrum system is one in which the transmitted signal is spread over a wide frequency band, much wider than the minimum bandwidth required to transmit the information being sent (see Figure 1-9). Band spreading is accomplished by means of a code which is independent of the data, called the spreading code. A reception synchronized to the code is used to de-spread and recover the data at the receiver.

Spread-spectrum communication systems are useful for suppressing interference, making secure communications difficult to detect and process, accommodating fading and multipath channels, and providing a multiple-access capability. Spread-spectrum signals cause relatively minor interference to other systems operating in the same spectral band. The two most common types of spread spectrum modulation are direct-sequence spread spectrum (DSSS) and frequency hopping spread spectrum (FHSS).

.In Frequency hopping Spread Spectrum (FHSS), the spectrum of a data-modulated carrier is widened by changing the frequency of the carrier periodically. Typically each frequency is chosen from a set of 2^k frequencies which are spaced approximately the width of the data modulation bandwidth apart. The frequency slots used to control the sequence of carrier frequencies are usually chosen pseudo-randomly by a code called FH sequence. Hence the transmitted signal appears as a data-modulated carrier which is hopping from one frequency to the next. In the receiver, the frequency hopping is removed by mixing (down-converting) with a local oscillator signal which is hopping synchronously with the received signal.

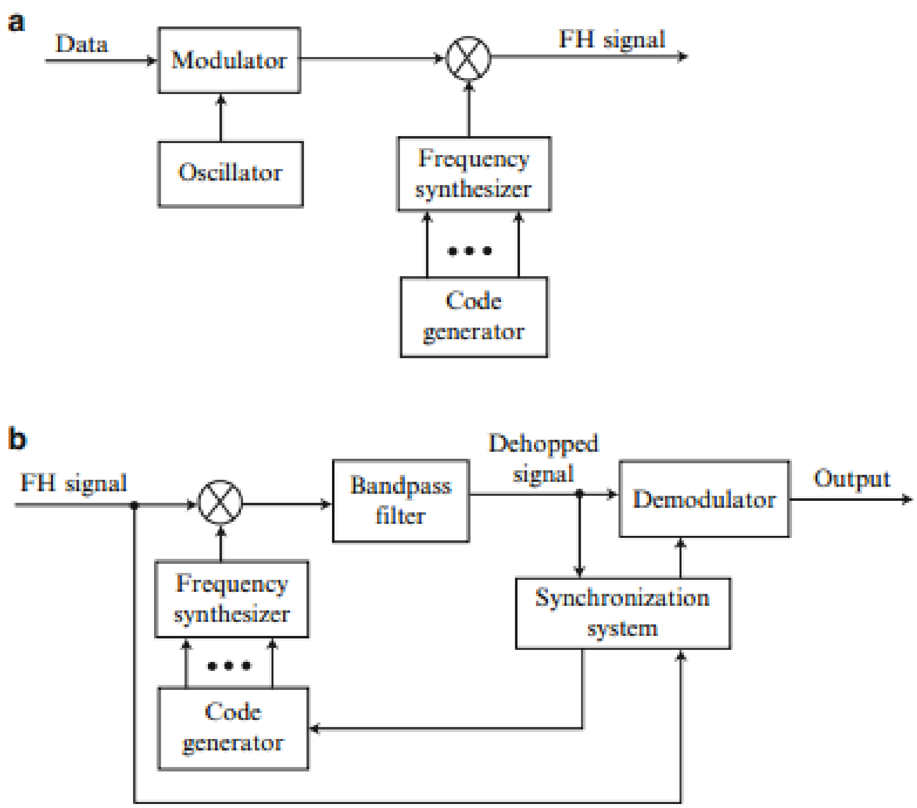

Figure 1.2: Block diagram of a typical Frequency Hopping (FH) system: (a) transmitter and (b) receiver

The time interval, or the slot in time for which the carrier frequency remains in a particular frequency slot is called the hopping interval. After every hopping interval, the carrier frequency is shifted to the next frequency slot in the FH sequence. In Figure 1.1 for example, there are 8 frequency slots, and the FH sequence is repeated after every 8 hopping intervals (time slots). The hopping is shown for 16 times slots, in which time, the FH sequence completes 2 cycles.

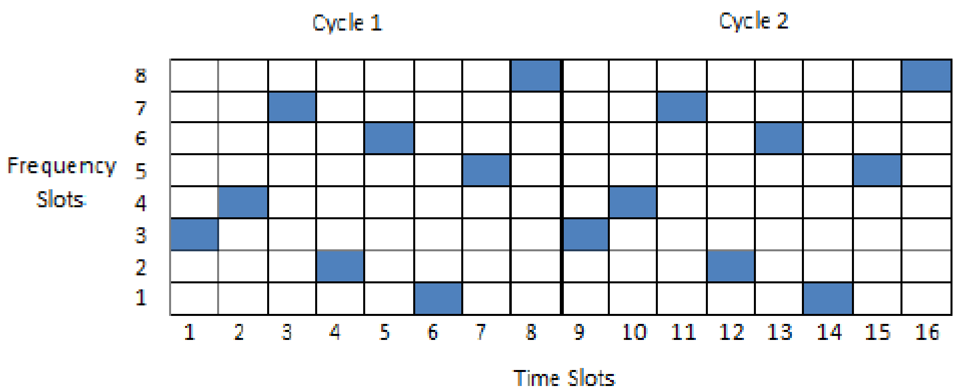

Figure 1.3: An illustration of frequency hopping

Emerged from military communications for their anti-jamming, secure and multi-access properties, frequency hopping spread spectrum techniques are now widely used in civil communications such as “Bluetooth” and ultra-wideband (UWB) communications.

1.3 Scope of the current work

The project deals with designing a frequency hopping scheme for an interference limited, asynchronous, multi-user OFDM system. Due to certain unique requirements of the system, the FH design is made using deterministic sequences, rather than pseudo-noise (PN) sequences. The idea of repeating the data in time domain and frequency domain is used to mitigate asynchronous interference in the system.

Chapter 2 outlines the basic considerations in the design of frequency hopping sequences. The need for using short deterministic sequences in the FH design is explained, and the design of deterministic FH sequences is dealt with in detail. Through a progression of three different schemes, an FH scheme that can support asynchronous users with multiple interferers is developed, through repetition of data in the frequency domain.

Chapter 3 deals with asynchronous interference mitigation in multi-user OFDM systems. It is shown that an asynchronous multi-user system leads to additional sources of induced Inter-carrier Interference (ICI), and a method to mitigate the same is presented, through the repetition of data in the time domain.

Chapter 4 outlines the OFDM system under consideration. The system requirements are listed and the system model is presented. Many of the ideas presented in chapters 2 and 3 are applied to the system in this chapter.

CHAPTER 2

Frequency Hopping Design

2.1 Why Frequency Hopping Spread Spectrum (FHSS)?

A spread-spectrum transmission offers three main advantages over a fixed-frequency transmission:

1) Resistance to jamming and eavesdropping: Due to spreading of the signal across a wide frequency range, an SS signal may simply appear as an increase in background noise to a narrowband receiver. An eavesdropper may have difficulty intercepting a transmission in real time if the pseudorandom sequence is not known.

2) Multiple Access Support: Spread spectrum signals add minimal noise to the narrowband frequency communications, and vice versa. As a result, an FHSS system can be designed for multiple user access.

3) Resistant to narrowband interference: The transmission occurs only on a small portion of the bandwidth at any given time, so that the effective interference bandwidth is much smaller than the total bandwidth of the system.

2.2 Frequency Hopping Sequences

FH sequences are used in multi-access spread spectrum communication systems as data modulation technique to specify which frequency is used for transmission at any given time slot.

2.2.1 Notation and Definitions

Let $F = \{f_0, f_1, ..., f_{l-1}\}$ be a set of frequencies available for the formation of frequency hopping sequences, which are, called an alphabet. Let S be the set of all sequences of length v over F. Any element of S is called a frequency-hopping sequence (FHS) of length v over F.

Given two FHSs $X, Y \in S$, we define their Hamming correlation as

$$H_{X,Y}(t) = \sum_{i=0}^{v-1} h[x_i, y_{i+t}], \qquad 0 \leq t < v$$

where $h[a,b]$=1 if a=b, and 0, otherwise, and all operations among the position incides are performed modulo v.

2.2.2 Auto- and Cross-correlation Properties

In a spread spectrum communication system, each sender transmits a message along with switching frequencies in every time slot according to an FH sequence $X \in S$ provided to him/her. FH sequences are often used periodically, i.e., they appear as $\ldots x_{l-2}, x_{l-1}, x_0, x_1 x_2$ ... The corresponding receiver then translates the received signals using the same FH sequence $X \in S$. Suppose that another sender wants to transmit another message over the same frequency library F, using another FH sequence $Y = \{y_0, y_1, \ldots, y_{l-1}\}$ from the same alphabet F starting at some time slot t. Then it may happen that the two senders transmit messages using the same frequency at the same time slot. If such signal interference occurs, then the messages transmitted at these time slots may be corrupted. Therefore it is generally desirable to keep the mutual interference, or the Hamming cross-correlations and the out-of-phase Hamming autocorrelations, as low as possible. In addition, it is also required that the frequency hopping signals have the in-phase Hamming autocorrelation as impulsive as possible so as to minimize any ambiguity about the source identity and the information in communication systems.

2.2.3 Design Considerations

FH sequence design normally involves six parameters: the size q of the frequency library F, the sequence length v, the family size M, the maximum out-of-phase Hamming autocorrelation H_a, and the maximum Hamming cross-correlation H_c. It is generally desired that the family of FH sequences has the following properties:

1) the maximum Hamming autocorrelation H_a should be as small as possible;

2) the maximum Hamming cross correlation H_c should be as small as possible;

3) the family size M for given H_a, H_c, q, and L should be as large as possible.

2.3 Need for Deterministic FH Sequences

2.3.1 Fast Acquisition

Spread spectrum communication requires that the transmitter and receiver spreading waveforms be synchronized. If the two waveforms are out of synchronization by as little as one chip, insufficient signal energy will reach the receiver data demodulator for reliable data detection. The task of achieving and maintaining code synchronization is delegated to the receiver. There are two components to the synchronization problem

1) Code acquisition – determination of the initial code phase
2) Code tracking – maintaining code synchronization after initial acquisition

In a frequency hopping spread spectrum (FHSS) system, a linear feed-back shift register (LFSR) is usually employed to generate pseudo-random or pseudo-noise (PN) sequences, which are then used to synthesize the frequencies that make up FH sequences. The time required for synchronization is directly proportional to the length of the PN sequence, used in the FHSS system. In systems, which are prone to often lose synchronization of the FH sequence at the receiver, due to malignant channel conditions, using long PN sequences is highly disadvantageous. But in systems which are required to support multiple users, a large family of PN sequences is needed along with good Hamming correlation properties, which necessitates the use of very long PN sequences.

Hence, to achieve fast acquisition, it is imperative that the FH sequences should be as short as possible.

2.3.2 Perfect Orthogonality

The orthogonality of FH sequences is critical for successful transmission of data, especially in systems which are interference limited. FH sequences that are generated using linear feed-back shift registers (LFSR) are pseudo-random in nature, and not perfectly orthogonal. There are PN sequence designs which achieve near orthogonality, but are not suited for the purpose of fast acquisition due to their very large lengths. Perfectly reliable communication can be achieved only with perfectly orthogonal FH sequences, which is in turn possible by employing deterministic sequences.

2.4 FH Design with Deterministic Sequences

2.4.1 Synchronous Transmission – Circularly Shifted Sequences

The need for fast acquisition and perfect orthogonality has led to the replacement of long PN sequences with short deterministic sequences.

The simplest way to achieve perfect orthogonality with the shortest possible sequence lengths is to use circularly shifted sequences. Figure 2.1 shows the family of circularly shifted sequences that can cater to a maximum of 8 users, while utilizing only 8 different frequencies (q = 8) to make up 8 distinct FH sequences (M = 8), of length l = 8.

User 1	1	2	3	4	5	6	7	8
User 2	2	3	4	5	6	7	8	1
User 3	3	4	5	6	7	8	1	2
User 4	4	5	6	7	8	1	2	3
User 5	5	6	7	8	1	2	3	4
User 6	6	7	8	1	2	3	4	5
User 7	7	8	1	2	3	4	5	6
User 8	8	1	2	3	4	5	6	7

Figure 2.1: A family of circularly shifted sequences for 8 users

The specifications for the circularly shifted FH sequences are as follows:

- Frequency alphabet, $F = \{1, 2, 3, 4, 5, 6, 7, 8\}$ with size q = 8
- Sequence length, $v = 8$ (i.e. each sequence occupies 8 time slots)
- Family size, $M = 8$ (encompassing a maximum of 8 users)
- Hamming correlation between FH sequences of users i and j ($i < j$) is given by:

$$H_{i,j}^{UB}(t) = \begin{cases} 8, & for\ t = (j - i) \\ 0, & otherwise \end{cases}$$

It can be seen that the hamming correlation of the sequences are discrete impulse functions, with the impulse occurring at different time slots for different pairs of users. Thus, any pair of sequences are perfectly orthogonal (i.e. have zero cross-correlation), except for a particular relative shift between them. Thus the design faces a serious issue, in that the sequences are perfectly orthogonal only when all the users are synchronized at the level of one hopping interval. Any asynchronicity between the users that is of the order of a hopping interval, can cause the sequences to overlap considerably, destroying the orthogonality, and hence the reliability of the system.

2.4.2 Asynchronous Transmission with Single Interferer – Data Repetition

For the case of asynchronous users, it was shown that the FH design scheme with circularly shifted sequences falls apart, due to the nature of the hamming correlation of the sequences. In this section, it is shown that the problem of asynchronicity can be overcome by repetition of the data in the frequency domain.

Consider a system with a maximum user requirement of 8 (like in the previous scheme). Le the bandwidth of the system be divided into two equal halves, henceforth called bands. Each band has 8 subcarriers (frequencies), with a total of 16 subcarriers in the entire bandwidth. Consider a scheme where each user is assigned two FH sequences, one in the upper band (UB) and the other in the lower band (LB). The user transmits two copies of identical data in both the bands, modulating them onto the corresponding subcarriers for the bands.

The FH sequence assignment for the users in both the bands is as shown in Figure 2.2. The sub-carriers in the upper band are indexed as 1, 2, 3, 4, 5, 6, 7 and 8, while those in the lower band are indexed as a, b, c, d, e, f, g and h. In the upper band (UB), each user is allocated an identical sequence of 8 sub-carriers belonging to the upper half, while in the lower band (LB), each user is allocated a circularly shifted variant of the same sequence of 8 sub-carriers belonging to the lower half.

	Lower Band Sequence								Upper Band Sequence							
User 1	1	2	3	4	5	6	7	8	a	b	c	d	e	f	g	h
User 2	2	3	4	5	6	7	8	1	a	b	c	d	e	f	g	h
User 3	3	4	5	6	7	8	1	2	a	b	c	d	e	f	g	h
User 4	4	5	6	7	8	1	2	3	a	b	c	d	e	f	g	h
User 5	5	6	7	8	1	2	3	4	a	b	c	d	e	f	g	h
User 6	6	7	8	1	2	3	4	5	a	b	c	d	e	f	g	h
User 7	7	8	1	2	3	4	5	6	a	b	c	d	e	f	g	h
User 8	8	1	2	3	4	5	6	7	a	b	c	d	e	f	g	h

Figure 2.2: FH design for 8 asynchronous users with data repetition

The specifications for the new FH design with data repetition are as follows:

- Upper band frequency alphabet, $F_{UB} = \{a, b, c, d, e, f, g, h\}$ with size $q_{UB} = 8$
- Lower band frequency alphabet, $F_{LB} = \{1, 2, 3, 4, 5, 6, 7, 8\}$ with size $q_{LB} = 8$
- Sequence length for both bands, $L_{UB} = L_{LB} = 8$
- Family size, $M = 8$ (encompassing a maximum of 8 users)
- Hamming correlations between FH sequences of users i and j $(i < j)$

$$H_{i,j}^{UB}(t) = \begin{cases} 8, & for\ t = 0 \\ 0, & otherwise \end{cases} \qquad \text{(in the upper band)}$$

$$H_{i,j}^{LB}(t) = \begin{cases} 8, & for\ t = (j - i) \\ 0, & otherwise \end{cases} \qquad \text{(in the lower band)}$$

This FH scheme with data repetition, assigning identical sequences in one band and circularly shifted sequences in the second band, has an important property as given below, which makes its usage possible in asynchronous multi-user systems.

Claim: For any pair of users in the current FHS design that are transmitting simultaneously with any relative delay, interference-free transmission happens at least in one of the two bands.

Proof: Consider the dot product of the hamming correlation function between FH sequences of any pair of users i and j ($i < j$).

$$H_{i,j}^{UB}(t).H_{i,j}^{LB}(t) = 0 \text{ for } 1 \le i < j \le 8 \text{ and } 0 \le t \le 7$$

From the above equation, it is seen that the hamming cross-correlation between FH sequences of any pair of users is zero, in at least one of the two bands, for any relative delay, ranging from $0 \le t \le 7$. Thus successful transmission without any coincidences happens in at least one of the two bands, when there is only one other interferer, corrupting the user's data.

Illustration: Consider two users, User1 and User6 transmitting simultaneously. From the point of view of User1, User6 is the only significant interferer. Figure 2.3 shows the scenario where both the users interfere with no relative shift. In this case, User1's FH sequence exactly coincides with that of User6 in the upper band, blocking User1's transmission completely. But in the lower band, User1 transmits successfully without any interference from the other user. Figure 2.4 shows the scenario where both the users interfere with a relative shift of 5 time slots (hopping intervals) between them. In this case, User1's data is corrupted in the lower band, while it is transmitted successfully in the upper band. For any other relative shift scenario, the data is transmitted without any interference in both the bands.

User 1	1	a	2	b	3	c	4	d	5	e	6	f	7	g	8	h
User 6	6	a	7	b	8	c	1	d	2	e	3	f	4	g	5	h

Figure 2.3: No relative shift between users: Upper band – User1 completely blocked by User6; Lower band – User1 transmits successfully

User 1	1	a	2	b	3	c	4	d	5	e	6	f	7	g	8	h
User 6	1	d	2	e	3	f	4	g	5	h	6	a	7	b	8	c

Figure 2.4: Relative shift of 5 time slots between users: Upper band – User1transmits successfully; Lower band – User1 completely blocked by User6

However, the scheme fails in the presence of more than 2 interfering users. For a particular set of relative delays, the data of a user in both the bands may be corrupted by two users that are transmitting simultaneously. One such scenario is depicted in Figure 2.5 where 3 users – User1, User5 and User6 are transmitting simultaneously. The relative shift between users 1 and 5 is 0 time slots, while that between users 1 and 6 is 5 time slots. In that case, User5 completely knocks User1's data in the upper band, and User6 completely knocks User1's data in the lower band. In effect, User1 fails to transmit both the copies of its data.

User 5	5	a	6	b	7	c	8	d	1	e	2	f	3	g	4	H
User 1	1	a	2	b	3	c	4	d	5	e	6	f	7	g	8	h
User 6	1	d	2	e	3	f	4	g	5	h	6	a	7	b	8	c

Figure 2.5: Three users transmitting simultaneously: Upper band – User1 completely blocked by User5; Lower band – User1 completely blocked by User6

Thus, it has been shown that, for the case of single interferer, the problem of asynchronous transmission among the users at the hopping interval level can be successfully tackled by the repetition of data in the frequency domain.

2.4.3 Asynchronous Transmission with Multiple Interferers – User Pairing

With the previous scheme of data repetition in the time domain, asynchronous interference from up to one user can be eliminated. For the case of multiple interferers, a modified form of the scheme, with user pairing can be used.

As shown in Figure 2.6, the 8 users in the previous system are now grouped into 4 pairs. Each pair of users gets a separate set of 8 subcarriers in each of the two bands. The system as a whole comprises of a total of 64 subcarriers (4 user pairs, 8 subcarriers per user pair per band and 2 bands). From the set of 8 subcarriers for each user pair, the users are assigned an identical FH sequence in the upper band, and circularly shifted sequences in the lower band. In this way, each user can transmit data successfully in at least one of the two bands, while still facing interference from the other user in the pair. Interference from users outside of one's own pair is avoided by allocating distinct frequencies for each user pair. The specifications for this FH design scheme are the same as that of the previous scheme in section 2.4.2.

	Lower Band Sequence								Upper Band Sequence							
User 1	1	2	3	4	5	6	7	8	33	34	35	36	37	38	39	40
User 2	2	3	4	5	6	7	8	1	33	34	35	36	37	38	39	40
User 3	9	10	11	12	13	14	15	16	41	42	43	44	45	46	47	48
User 4	10	11	12	13	14	15	16	9	41	42	43	44	45	46	47	48
User 5	17	18	19	20	21	22	23	24	49	50	51	52	53	54	55	56
User 6	18	19	20	21	22	23	24	17	49	50	51	52	53	54	55	56
User 7	25	26	27	28	29	30	31	32	57	58	59	60	61	62	63	64
User 8	26	27	28	29	30	31	32	25	57	58	59	60	61	62	63	64

Figure 2.6: FH design for 8 asynchronous users with user pairing

2.4.4 Summary of FH Design Schemes with Deterministic Sequences

Over the course of three schemes, we have developed a frequency hopping scheme using deterministic sequences that can support multiple users transmitting asynchronously, with any number of interfering users. All the three schemes listed in the previous sections support a maximum of 8 users, and use deterministic sequences of length 8. As the number of subcarriers in the system is increased, additional functionality is introduced in the system. The evolution of the three schemes is shown in Table 2.1

Scheme	Total Number of Subcarriers	Features	Technique
Sec 2.4.1	8	Synchronous users only	Circularly shifted sequences
Sec 2.4.2	16	Asynchronous users with up to one interferer	Data repetition in the frequency domain
Sec 2.4.3	64	Asynchronous users with multiple interferers	Data repetition in the frequency domain, user pairing

Table 2.1: Comparison of three FH design schemes with deterministic sequences

CHAPTER 3

Asynchronous Interference Mitigation

3.1 Asynchronous Interference

Asynchronism inherently exists in many communication systems mainly due to the effect of multi-path and propogation delay. As a fundamental issue in design of communication systems, the asynchronism can detrimentally affect the system performance if it is ignored or not dealt with properly.

The users in an OFDMA system using frequency hopping for the orthogonal allocation of subcarriers can be asynchronous at the level of a hopping interval (the time for which the user's subcarrier frequency remains constant at a particular frequency slot) or at the level of an OFDM symbol.

3.1.1 Asynchronous Interference at the level of a hopping interval

Asynchronicity among the users in a frequency hopped OFDM system at the level of a hopping interval is dealt with by appropriately choosing FH sequences to be orthogonal or nearly orthogonal for any amount of relative delay. The maximum hamming cross-correlation between any pair of sequences in a family should be as small as possible to avoid this asynchronous interference.

In section 2.3 we have looked at various schemes of FH designs which use deterministic sequences to avoid interference from asynchronous users. A major technique that has been used to achieve this is to repeat the data in the frequency domain i.e. to transmit 2 copies of the same data in two halves of the bandwidth simultaneously. Although it reduces the spectral efficiency of the system, it increases the redundancy in the system, and adds to frequency diversity.

3.1.2 Asynchronous Interference at the level of an OFDM Symbol

The dominant sources of interference in a multiuser OFDM system are multiple access interference, co-antenna interference which is the interference caused by the signals from multiple transmit antennas of a given user being received on the same receive antenna, and inter-carrier interference (ICI). In particular, ICI has a number of sources. One form of ICI is created when the delay spread of the channel is longer than the cyclic prefix, which is used to guard against dispersion from adjacent OFDM symbols. Usually, OFDM systems employ a sufficiently long cyclic prefix to avoid these problems.

More importantly, in multiuser OFDM systems, the asynchronicity between users, which is caused by the different propagation distances between users and the receiver, can create an additional source of ICI when the delay differences between users are of the order of an OFDM symbol. In such cases, even though the cyclic prefix is longer than the delay spread of the channel, it may not be long enough to deal with ICI caused by the interfering user. The channel dispersion from the interfering user may corrupt the data of the desired user.

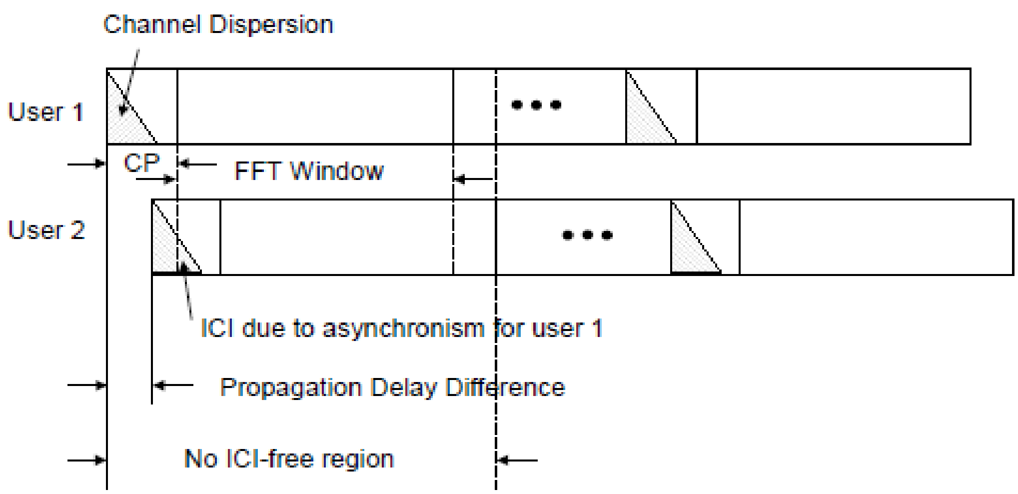

Figure 3.1: Induced ICI due to asynchronous user at OFDM symbol level

As the relative shift between the asynchronous users varies from 0 to N + CP, where N is the number of subcarriers and CP is the length of the cyclic prefix, the presence of induced ICI due to the interfering users varies as follows:

- For $0 \leq Shift \leq CP - DS$, there is no ICI
- For $\mathrm{CP} - \mathrm{DS} \leq Shift \leq N + CP$, there is ICI

(CP – Cyclic Prefix; DS – Delay Spread)

As can be seen from Figure 3.2 that is plotted based on the above mentioned observations, it can be seen that for most of the delay scenarios, induced ICI is seen due to asynchronous interference.

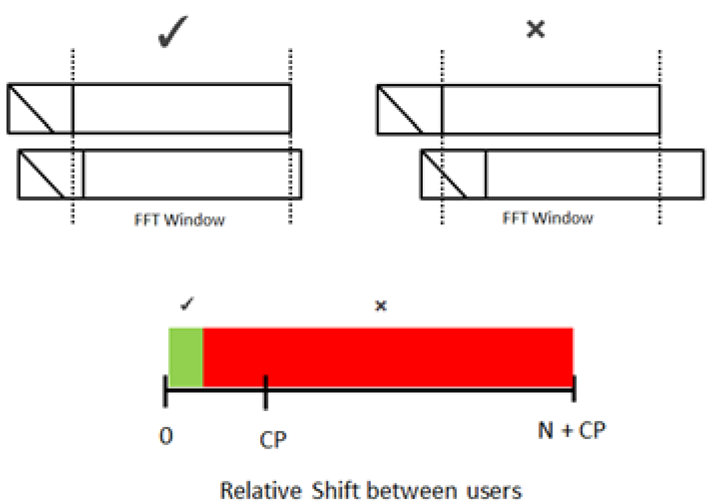

Figure 3.2: Induced ICI due to asynchronous user for various relative shifts

3.2 Interference Mitigation with Repeated Symbols

Similar to how the asynchronous interference at the level of hopping interval in FH systems is mitigated by repeating the data in the frequency domain, it is possible to mitigate the asynchronous interference at the level of symbol time by repeating the data in the time domain.

The new sub-frame structure for the modified scheme is shown in Figure 3.3. As shown in the figure, the OFDM symbol is repeated 2 times in each sub-frame and then appended with a cyclic prefix. So, the net length of the modified sub-frame will be 2N + CP, almost twice as long as is usual. Although the data rate is reduced by half with this scheme, the time-domain symbol repetition adds to time-diversity and redundancy of the system.

CP	OFDM Symbol	OFDM Symbol

Figure 3.3: Modified sub-frame structure with OFDM symbol repetition

3.2.1 Optimal Choice for the FFT Windows

In OFDM systems, at the receiver side, a part of the received signal corresponding to the CP may be discarded before the signal is demodulated by the FFT. The issue of determining which part of the signal should be discarded and which part should be input to the FFT is commonly referred to as time synchronization. Thus, time-synchronization is typically referred to as the problem of finding the moment in time when to sample a signal in order to obtain as good performance as possible. There exist several algorithms for efficiently choosing the placement and positioning of the FFT window at the receiver, like the Schmiddle Cox algorithm.

In the current setup, since the data is repeated twice in the time domain, it is possible to extract 2 OFDM symbols from one sub-frame. This translates to choosing two independent FFT windows, at the receiver, to extract the data. Once the symbol boundary is identified at the receiver by a timing synchronization algorithm, unlike in a conventional OFDM sub-frame (which has only one FFT window N samples wide), there still exist several choices for the two FFT windows in the revised sub-frame structure. Figure 3.4 depicts three such choices for the two FFT windows. They are:

1) FFT Window 1: From CP to N + CP
2) FFT Window 2: From N + CP to 2N + CP

3) FFT Window3: From CP/2 to N + CP/2

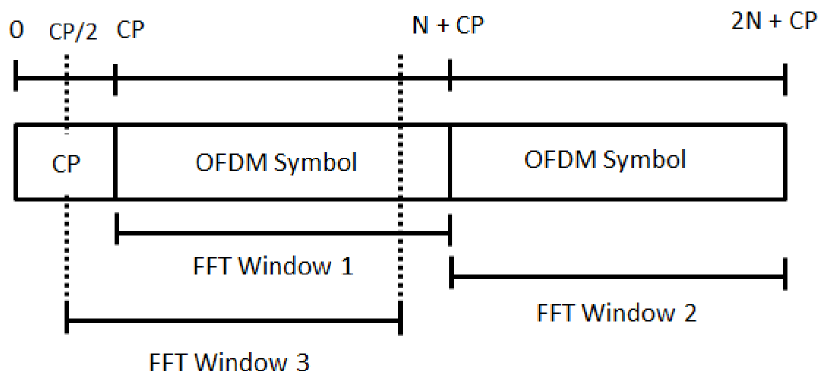

Figure 3.4: Three choices of FFT windows for the modified sub-frame structure

For each of the three FFT windows depicted in Figure 3.3, the presence/absence of induced ICI due to an asynchronous user, for each of the relative shift that is possible between two asynchronous users ranging from 0 to 2N + CP, for the modified sub-frame structure, is shown in Figure 3.5.

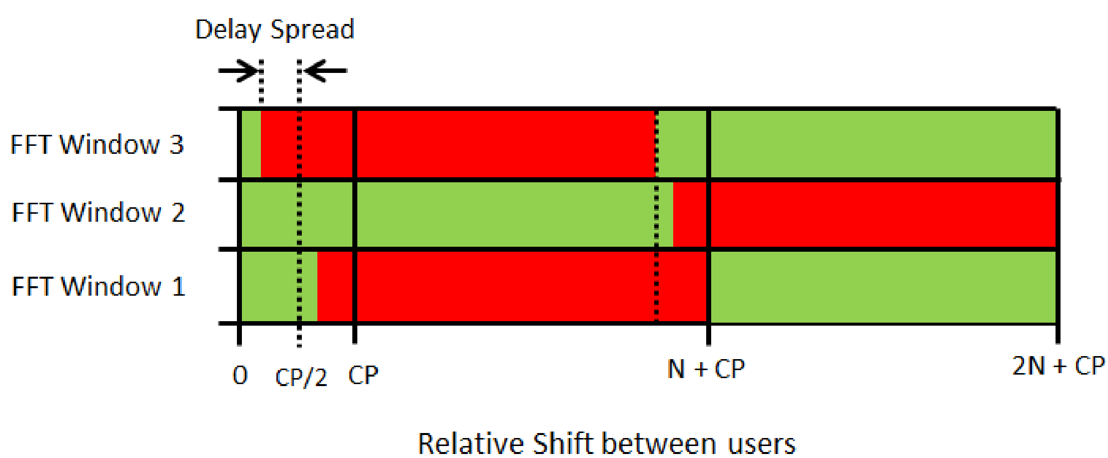

Figure 3.5: Induced ICI due to asynchronous user for various relative shifts between users

From the Figure 3.5, it can be seen that each of the three FFT windows faces asynchronous interference only when the relative shift between users is in a certain range. It can also be observed that the width of this range is constant for all of the 3 FFT windows, and that is equal to N + DS, where N is the number of samples in each OFDM symbol and DS is the delay spread of the channel. It can be explained as follows: Since the length of the modified sub-frame that is corrupted by channel dispersion is DS (delay spread of the channel), any window of width N in the sub-frame gets obstructed for a range of relative shifts of width N + DS. Another important point to be noted is that the Figure 3.4 is depicted for the case when the delay spread is less than half of the length of cyclic prefix, i.e. when $\mathrm{DS} \leq \frac{CP}{2}$.

Because the asynchronous interference is only seen for selective ranges of relative shifts between users for each of the FFT windows, it becomes possible to cleverly choose a couple of independent FFT windows, so that at least one of the two OFDM symbols in each sub-frame is free from the induced ICI. The ranges of relative shifts wherein clean data is obtained at each FFT window, is listed in Table 3.1.

From the Table 3.1, it can be seen that if FFT windows 2 and 3 were chosen to extract the two identical OFDM symbols from the modified sub-structure, then for $\mathrm{DS} \leq \frac{CP}{2}$:

- For relative shifts in the range, [0, N + CP/2], interference free data can be obtained at FFT window 2
- For relative shifts in the range, [N + CP/2, 2N + CP], interference free data can be obtained at FFT window 3

Key inferences:

- If $\mathrm{DS} \leq \frac{CP}{2}$ then asynchronous interference from the other user can be completely eliminated using FFT Window 1 and FFT Window 2.
- If $\mathrm{DS} > \frac{CP}{2}$ then asynchronous interference cannot be eliminated, even with the repetition of data symbols.

Hence, as long as the delay spread is within half of the length of cyclic prefix, interference-free data is obtained at least at one of the two copies of data that is repeated in the time domain.

FFT Window	Window Interval	Relative shift rage for clean data	Relative shift range for corrupted data
1	[CP, N + CP]	[0, CP – DS] [N + CP, 2N + CP]	[CP – DS, N + CP]
2	[N + CP, 2N + CP]	[0, N + CP – DS]	[N + CP – DS, 2N + CP]
3	[CP/2, N + CP/2]	[0 CP/2 – DS] [N + CP/2 2N + CP]	[CP/2 – DC, N + CP/2]

Table 3.1: Comparison of the 3 FFT windows

CHAPTER 4

The OFDM System

4.1 System Requirements

The OFDM system under consideration is unlike a conventional cellular communication system in many ways. Firstly, there is no dearth of availability of bandwidth, and secondly, the number of users in the system is comparatively small. Also, the obstacles are less complex than a typical outdoor wireless environment, and there is almost always a direct line of sight path from the transmitter to the receiver. The system is expected to fulfill certain unique requirements:

- Asynchronous transmission in multi-user environment: The bandwidth can be used by a number of users at the same time, without any prior notification. Thus, users are asynchronous, which can lead to inter block interference (IBI).
- Robustness to Jamming: The system finds use in defense related aeronautical applications, which require it to be immune to security threats like eaves dropping and jamming.
- Very high Doppler: The OFDM link is expected to function in a high Doppler environment with transceiver speeds ranging 1000 km/hour
- Support to variable data rates: The system is capable of operating at three different ranges of data rates – Low Bit Rate (LBR), Medium Bit Rate (MBR) and High Bit Rate (HBR).
- Resistance to interference: The transmitters are in constant motion at very high speeds, with multiple such transmitter-receiver pairs in the vicinity, leading to strong interference.

Hence, the system model is different from that of a conventional OFDM system, to cater to the several requirements of the system.

4.2 System Design

4.2.1 Subcarrier Mapping

The bandwidth of the system is divided into 256 sub-carriers, indexed from -127 to 128. The bandwidth is hierarchically divided into bands, blocks and tiles, the details of which are given below.

Bands

The total bandwidth is divided into 2 equal halves: the upper band (UB) and the lower band (LB), each of which has 128 sub-carriers each. The data is transmitted twice by each user, once in the upper band and once in the lower band. For this purpose, each user is assigned a certain number of sub-carriers in both upper band and lower band.

The division of bandwidth into bands aids in the jamming performance of the system. Due to the large bandwidth of the system, a narrowband jammer can at most block only a part of one of the two bands. Since, the data is repeated in both the bands, successful transmission is assured in at least one of the two bands.

Another advantage of this division is the asynchronous interference mitigation at the level of hopping interval. As detailed in Section 2.4.2, repeating the data in frequency domain can be used to support asynchronous users, with up to one interferer, wherein interference-free data transmission happens in at least one of the bands.

Blocks

Out of the 256 subcarriers in the system, every 16^{th} subcarrier is allotted to the wideband preamble. Hence, there exist contiguous groups of 15 subcarriers for carrying data between two preamble subcarriers. This group of 15 subcarriers is termed as a block. There are 7 such blocks per band.

As seen in Section 2.4.3, support for asynchronous users with more than one interferers, requires user pairing. The division of bands into blocks caters to this need. Each user pair is assigned one block from each of the two bands. Within a block, the two users in a pair use different hopping sequences, so as to ensure interference-free communication in at least one of the bands.

Tiles

The subcarriers under each block are grouped under 3 tiles, with 5 subcarriers forming a single tile. A tile is the fundamental unit of hopping for each user. Each user hops among the tiles that belong to the block assigned to him. The users are paired, and each user receives 2 hopping sequences to hop among the tiles, one sequence for the upper band's block and another for the lower band's block. As detailed in Section 2.4.3, the sequences are designed to ensure clean transmission without interference in a least one band.

The grouping of tiles into blocks can also be varied to suit to the variable data-rate requirements of the system. As the number of tiles in each block is reduced, the number of blocks in each band can be increased, which can be used to slightly rearrange the sub-carrier mapping to support more number of users.

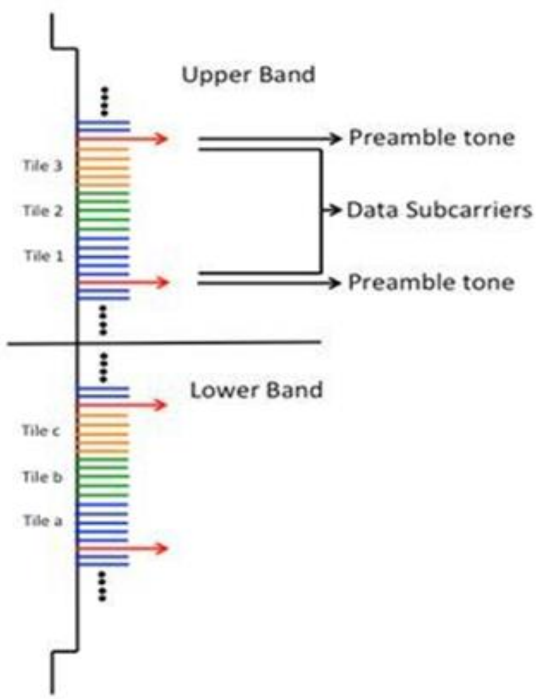

Figure 4.1: Subcarrier mapping for the OFDM system

4.2.2 Frequency Hopping

As mentioned previously, frequency hopping is done by the users at the tile level. The users are paired and each pair is assigned one block from each of the upper and lower bands. Each user is assigned 2 FH sequences, to hop among the tiles of the respective blocks in both the bands. An illustration of frequency hopping for a pair of users is shown in Figure 4.2.

Upper Band	Block 1			
	User 1	Tile 1	Tile 2	Tile 3
	User 2	Tile 1	Tile 2	Tile 3
Lower Band	Block 2			
	User 1	Tile 4	Tile 5	Tile 6
	User 2	Tile 5	Tile 6	Tile 4

Figure 4.2: Frequency hopping in a pair of users

In the upper band, both the users in the pair are assigned the same hopping sequence of tiles, while in the lower band the sequences are circularly shifted versions of one another. This scheme of hopping ensures that, for any relative delay between the two users, at least one copy of the data is assured to be free of interference.

4.2.3 Frame Structure

The time domain frame is designed so as to mitigate asynchronous interference at the symbol level. Every frame has a preamble in the first symbol, followed by 3 data symbols, a pilot symbol, and 3 more data symbols. Each sub-frame is made of two copies of the OFDM symbol appended to a cyclic prefix. As shown in Section 3.2, this repetition of data in time domain ensures that at least one copy of data is free of the induced ICI due to an asynchronously interfering user. The frame structure is shown in Figure 4.3.

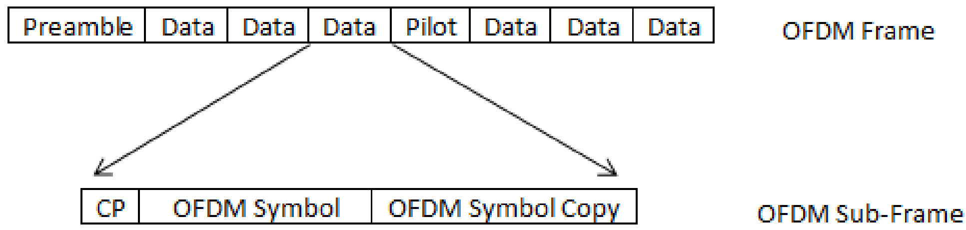

Figure 4.3: OFDM Frame structure

4.3 Variations in the Design

The design offers enormous flexibility in two main terms

1) Maximum number of users that can be supported: This is achieved by changing the number of tiles per block. A rearrangement of the subcarrier mapping to have lesser number of tiles per block increases the total number of blocks available to the users. As each user is allocated one block per band, more number of users can be supported with more number of blocks.
2) Maximum data rate per user: This is achieved by changing the number of blocks allocated to each user. A user with high data rate requirement can be assigned more than one block per band, thus increasing the data rate by transmitting independent data in different blocks.

Table 4.1 shows three different scenarios, each supporting different number of users. As can be observed from the table, as the number of tiles per block is reduced, the maximum number of users that can be supported increases. Another point to note is that, the percentage of bandwidth occupied also increases with the number of users in the system.

No. of tiles per Block	No. of Blocks in each band	Percentage of bandwidth occupied	No. of users supported
4	5	25%	10
3	7	33%	14
2	11	50%	22

Table 4.1: Various Schemes to support different number of users

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