DESIGN OF MULTIHOP PACKET RADIO NETWORKS

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ABSTRACT

Up to now, almost all Packet Radio Network (PRN) protocols assume omnidirectional antenna for receiving and transmitting signals. However, using directional transmitting antennas might have the advantage of having the network throughput increased by a greater spatial-reuse of the channel. We investigate this possibility in a multihop PRN.

We first analyse the performance of Slotted ALOHA with Multiple Directional Antennas (SA/MDA). The one-hop throughput of SA/MDA in a network with randomly distributed stations is evaluated. The same analysis is given for a deterministic lattice network. We also examine the expected progress of a packet when the Most Forward within R (MFR) routing strategy is used. When compared to the single omnidirectional transmitting antenna case, the throughput gain could be as much as the number of directional antennas used.

Next, we propose a new protocol for multihop PRNs termed as Multi-Tone multiple access with Collision Detection using Multiple Directional Antennas (MTCD/MDA). An acknowledging scheme using Extended Busy tone (EB/ACK) suitable for the MTCD/MDA protocol is also introduced. We analyse the slotted non-persistent version of MTCD/MDA for randomly distributed stations and deterministic lattice networks. Numerical results

show that the one-hop throughput is also proportional to the number of directional transmitting antennas used. With four directional antennas used, the throughput of the MTCD/MDA protocol is about three times the SA/MDA protocol.

無線電訊包網絡的設計

摘要

現在的無線電訊包網絡大多使用全向天線接收及發送信號，但使用定向傳輸天線卻可以利用通道的空間重用現象來增加網絡的通訊效率。本文將研究定向傳輸天線在多段無線電訊包網絡的應用情況。

我們首先分析使用多支定向傳輸天線的時分ALOHA協議(SA/MDA)的運作特性。我們計算了隨機分佈網絡和固定陣點網絡的單段通訊效率。此外，還找出了採用MFR路徑選擇方法時的訊包前進期望值。當與使用單支全向傳輸天線的系統比較，SA/MDA的通訊效率增益可以達到和定向天線的使用數目相若。

其次，我們提出了一種全新的多段無線電訊包網絡協議，簡稱為 MTCD/MDA，並介紹適合此協議的伸延繁忙音調認收規程(EB/ACK)。我們分析了時分非堅持 MTCD/MDA 協議應用於隨機分佈網絡及固定陣點網絡的運作特性。分析結果顯示此協議的單段通訊效率亦是隨著定向天線的使用數目增長。當使用四支定向傳輸天線時，MTCD/MDA 協議的通訊效率大概是 SA/MDA 協議的三倍。

ACKNOWLEDGEMENT

The author would like to express his sincere gratitude to his thesis supervisor, Dr. T. S. Yum for his patient guidence and valuable suggestions during the course of research.

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CHAPTER 1

INTRODUCTION

Since the evolution of the ALOHA system [1] at the University of Hawaii, Packet Radio Networks (PRNs) have become an attractive field of research. The basic idea of an ALOHA system is to let the users transmit whenever they have data to be sent. If a collision occurs, the packet will be retransmitted after a random delay. Roberts proposed a slotted version, referred as Slotted ALOHA [2], that can double the channel capacity. In Slotted ALOHA, time is divided into slots of duration equal to the packet length. Each user is required to start the transmission of its packets at the beginning of the slot only.

Later, Tobagi and Kleinrock developed the Carrier Sense Multiple Access (CSMA) protocol [3] which is suitable for the network with low end-to-end propagation delay compared to the packet transmission time. In CSMA, users must listen to the broadcast channel before transmitting, and inhibit transmission if the channel is sensed busy. According to the action that a terminal takes to transmit a packet after sensing the channel, there are two main versions, namely the nonpersistent and p-persistent CSMA [3]. One improved modification is the Carrier Sense Multiple Access with Collision Detection (CSMA-CD) [5]. In this protocol, terminals also monitor the channel during transmission and abort the transmission if a collision is detected. However CSMA/CD is not suitable for radio channels since a station cannot transmit and receive at the same time.

Besides the ALOHA and CSMA, many protocols have been proposed and analysed [6] [21].

When the area of communication becomes larger, a multihop system is needed to connect all stations in the network. The main research effort on such multihop networks is at increasing the network throughput by spatial-reuse of the radio channel. Since a transmitted packet is received by only some of the stations in the network, there is a chance that another station in a different location may also be successfully transmitting a packet during the same time. Some results in the case of two-hop PRNs with particular topology and traffic patterns for ALOHA [7] and nonpersistent CSMA [8] have been obtained by Tobagi. The performance of the Slotted ALOHA protocol in multihop environment has been studied in [11] [12] and the work was generalized to environment where radio receivers have the ability to capture signals [13]. Boorstyn and Kershenbaum have analysed the performance of multihop PRNs operating under CSMA with perfect capture using an exact Markov procedure for exponentially distributed packet lengths [9]. In [10], the procedure was generalized for arbitrary packet length distributions with rational Laplace transforms.

The spatial reuse of the channel improves the throughput of the network. However, since the purpose of transmitting packets in a multihop environment is to advance them towards their destinations, a more appropriate measure of performance is the expected one-hop progress of a packet in the desired direction [11]. In [14], the optimal transmission range is found for Slotted ALOHA (with and without capture) and nonpersistent CSMA.

In the multihop environment, using carrier sensing protocols can only provide information about the transmitter's local environment. Hence hearing the channel idle does not guarantee that the receiver's environment is also idle. In order to avoid collision at the receiver, Busy-Tone Multiple Access (BTMA) protocol can be used [4]. As soon as the receiver detects a packet being transmitted to it, it broadcasts a busy-tone to prohibit its neighbours to transmit. Roy and Saadawi [15] have proposed a nonpersistent Carrier Sense Multiple Access with Busy Tone and Collision Detection (CSMA/BT-CD) scheme for multihop PRNs. A station will start transmission of packets if and only if the data channel as well as the busy-tone channel are sensed idle. They have analysed the performance of CSMA/BT-CD for a three-node chain network [15] and a five-node uniform ring network [16].

The main advantages of packet radio networks [21] over conventional networks is that they are not dependent on fixed topologies, are easy to establish, and can operate unattended. These characteristics allow terminals to be mobile. Sinha and Gupta [17] studied a "stop and wait" type protocol for mobile packet radio networks. They derived the throughput and delay performance for that protocol in a fading additive white Gaussian noise (AWGN) channel. The throughput and delay for CSMA and

CSMA/CD were also derived for the same channel type [18] [19].

Up to now, almost all the PRN protocols assume omnidirectional antenna for receiving and transmitting signals. This is due mainly to the simplicity requirement of the system and the protocol. Using directional transmitting antennas however has the advantage that a packet is received by a smaller set of stations in a certain direction, resulting in smaller transmission interference. This means greater spatial-reuse of the channel and leads to a higher throughput of the network.

The network considered here consists of a large number of relocatable stations/repeaters and a still larger number of possibly mobile terminals distributed randomly in a large geographic area. The protocols proposed in this thesis is for the communication between these relocatable stations. Other protocols [6, 17-21] that are needed for the communication between two terminals and between a terminal and a station are not considered here. Stations are assumed to be stationary when transmitting packets so that directional antennas can be installed in specific orientations.

In Chapter 2 of this thesis, we first evaluate the one-hop throughput of Slotted ALOHA with Multiple Directional Antennas (SA/MDA) in a multihop PRN with randomly distributed stations. We then extend the analysis to a deterministic lattice network. A second performance measure , the expected progress of a packet

[14], is also evaluated; and comparsions are made to the omnidirectional antenna protocols. In Chapter 3, a new protocol suitable for the multihop PRNs termed as Multi-Tone multiple access with Collision Detection using Multiple Directional Antennas (MTCD/MDA) is introduced. Since acknowledgement needs to be explicitly carried out in a multihop environment, a suitable acknowledging scheme is also designed for the MTCD/MDA protocol. In Chapter 4, we analyse the slotted non-persistent version of MTCD/MDA. Numerical results are given and the performance is compared to SA/MDA.

CHAPTER 2

THE SA/MDA PROTOCOL AND ANALYSIS

In this chapter, we first outline the system requirement for multihop PRNs using multiple directional antennas. Secondly, we will evaluate the performance of SA/MDA. The Slotted ALOHA protocol for Single Omnidirectional Antenna statons (SA/SOA) was studied by Takagi and Kleinrock [14]. We generalize the protocol and its throughput analysis for use with multiple directional transmitting antennas. The one-hop throughput of SA/MDA is evaluated for randomly and deterministic distributed stations. We also examine the expected progress of a packet when the Most Forward within R (MFR) routing strategy [14] is used.

2.1 System Requirements

For the multihop packet radio network discussed in this thesis, we assume that all the physical locations of the stations in the network are known and fixed. Each station has a "map" indicating the locations of all other stations. Each station has an omnidirectional antenna for receiving signal and four directional antennas with 90 degree broadcasting angle each for transmission. The pointing directions of the antennas are the same for all stations. All stations in the network use the same frequency band for transmitting packets. Let all stations transmit with the same power and let R be the transmission range. Let the circle of coverage be divided into four quadrants

(Figure 2.1). Antenna k (k =1,2,3,4) is responsible for the transmission of packets to stations in quadrant k.

When a station wants to send a packet to another station, it needs to know the location of its destination and choose the suitable antenna for transmission. Hence we assume that each station keeps a direction table which assigns each of its neighbours a transmitting antenna pointing to it. Table 2.1 shows a typical direction table for station S of Figure 2.2. Note that some stations, e.g. station C, F, H and I are assigned with two antennas since they are located near the boundary of the quadrants. Both antennas are excited when packets are transmitted to these stations. When a new station is set up in the network, besides constructing the direction table for the new station, the direction tables of its neighbours need also be updated.

We assume that all packets are of the same length and occupy one slot time. Before transmission, a station chooses the suitable antenna by searching the direction table and starts transmission at the beginning of the next slot. If collision occurs, the station retransmits the packet after a random delay. Packet propagation delays are assumed to be negligible compared to the transmission time and traffic acknowledgement is carried on a separate channel.

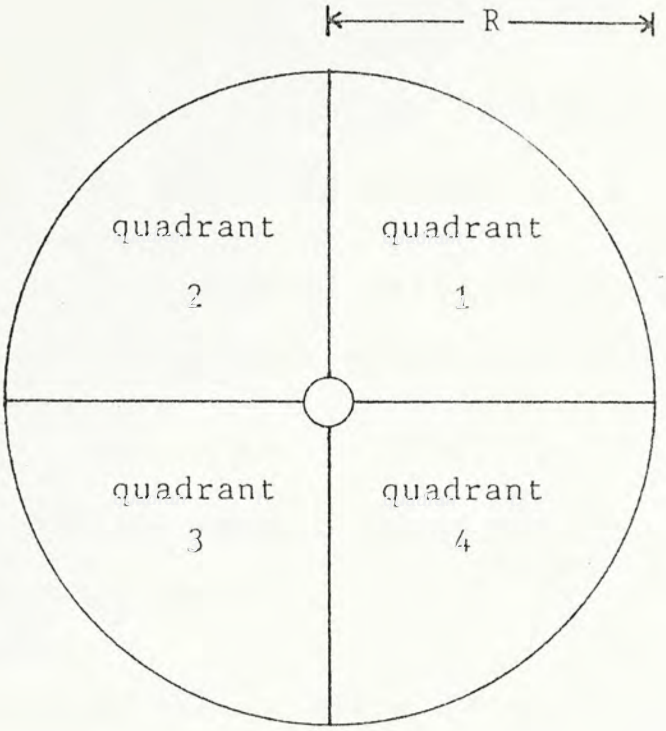

Figure 2.1 The antenna quadrants.

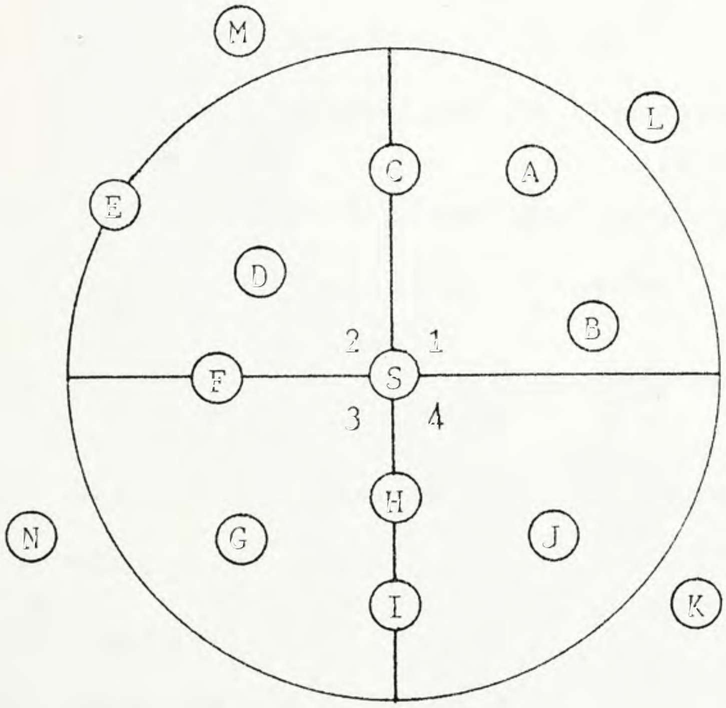

Figure 2.2 The neighbours of station S.

Neighbour Station	Antenna Number
A	1
B	1
C	1,2
D	2
E	2
F	2,3
G	3
H	3,4
I	3,4
J	4

The direction table of station S

Table 2.1

2.2 The One-Hop Throughput of SA/MDA

To analyse the performance of SA/MDA, we will make the following assumptions about the network :

(1) The spatial distribution of stations is a two-dimensional Poisson distribution with an average of λ stations per unit area.

(2) All stations in the network transmit with the same power on the same frequency band.

(3) The fixed transmission radius is R and the transmission circle is assumed to be perfect.

(4) At each station, the probability of transmitting a packet at any particular slot is p, a constant.

(5) The probability of sending packet to any particular neighbouring station is the same.

(6) The channel is noiseless; unsuccessful transmission is only due to the collision of packets.

(7) The locations of the immobile stations are known.

(8) When the final destination is outside the transmission circle, the transmitting station sends the packet to the station most forward in the direction of the final destination (MFR routing).

Let $N \triangleq \lambda \pi R^2$ be the average number of stations in a circle of radius R and S(p,N,m) be the one-hop throughput of a station with m directional transmitting antennas. This throughput is defined as the average number of successful transmissions per time slot from a station. In SA/MDA the number of directional antennas m can be any positive integer although in most cases we take four as a typical example.

Consider the transmission of a packet from P to Q (Q is a neighbouring station of P). Let A_i be the event that there are i other stations (excluding the transmitter P and receiver Q) in the receiving range of Q. Then from the Poisson assumption of station distribution,

$$\text{Prob}[A_i] = \frac{N^i}{i!} e^{-N} \qquad i = 0,1,2,\ldots \tag{2.1}$$

Let B be the event that the transmission from P to Q is successful. We have

$$\begin{aligned} \text{Prob}[B|A_i] &= \text{Prob}[\text{all } i \text{ neighbours of Q (excluding P) do not} \\ &\qquad \text{transmit towards Q's direction}] \\ &\quad \cdot \text{Prob}[\text{Q does not transmit}] \\ &= (1-p/m)^i \, (1-p) \quad . \end{aligned} \tag{2.2}$$

Thus we have

$$S(p,N,m) = \text{Prob[there is at least one station within R]} \cdot \text{Prob[P transmits]} \cdot \text{Prob[B]}$$

$$= (1-e^{-N})\, p \sum_{i=0}^{\infty} \text{Prob}[B|A_i]\cdot\text{Prob}[A_i]$$

$$= (1-e^{-N})\, p \sum_{i=0}^{\infty} [(1-p)(1-p/m)^i][\frac{N^i}{i!}e^{-N}]$$

$$= p(1-p)(1-e^{-N})e^{-pN/m} \qquad (2.3)$$

$$= \begin{cases} p(1-p)N & \text{as } N \to 0\ , \\ p(1-p)e^{-pN/m} & \text{as } N \to \infty\ . \end{cases}$$

For a given set of N and m, S(p,N,m) is maximized by setting p to

$$p^* \triangleq \frac{2m}{(N+2m) + \sqrt{N^2+4m^2}} \qquad (2.4)$$

$$= \begin{cases} 1/2 & \text{as } N \to 0, \\ m/N & \text{as } N \to \infty . \end{cases}$$

Using p*,

$$S(p^*,N,m) = \frac{m(1-e^{-N})}{2m+\sqrt{N^2+4m^2}} \quad \exp(-\frac{2N}{(N+2m)+\sqrt{N^2+4m^2}}) \qquad (2.5)$$

$$= \begin{cases} N/4 & \text{as } N \to 0\ , \\ m/(Ne) & \text{as } N \to \infty . \end{cases}$$

When m=1, the above result degenerates to those in [14]. We define the m-antenna throughput gain to be

$$r(m) \triangleq \frac{S(p,N,m)}{S(p,N,1)} = e^{pN(1-1/m)} \qquad (2.6)$$

Here, r(m) > 1 for m >=2; hence the throughput of SA/MDA is always higher than that of SA/SOA. If p=1/N, which corresponds to setting the average traffic load (including retransmission traffic) to be equal to one packet per slot within the transmission range, then when m=4, r(m)=2.117. If the optimum p is used,

$$r^*(m) = \frac{S(p^*,N,m)}{S(p^*,N,1)}$$

$$= \frac{2m+m\sqrt{N^2+4}}{2m+\sqrt{N^2+4m^2}} \exp\left(\frac{2N}{N+2+\sqrt{N^2+4}} - \frac{2N}{(N+2m)+\sqrt{N^2+4m^2}}\right) \qquad (2.7)$$

$$= \begin{cases} 1 & \text{as } N \to 0, \\ m & \text{as } N \to \infty, \end{cases}$$

which says that when the transmission range is small, using multiple directional antennas offers no improvement of throughput. When the transmission range increases, the throughput gain could be as much as the number of directional antennas used.

We now assume the spatial distribution of stations to be a deterministic lattice (see Figure 2.3). Then the number of stations in a circle of radius R is a fixed number N. Following a similar procedure, we get

$$S(p,N,m) = p(1-p)(1-p/m)^{N-2} \qquad N >= 2 \qquad (2.8)$$

for deterministic lattice distribution. For a given set of N and m, S(p,N,m) is maximized by setting p to

$$p^* \triangleq \frac{2m}{(N-1)+2m+\sqrt{(N-1)^2+4m(m-1)}} \qquad N >= 2 \qquad (2.9)$$

$$= m/N \qquad \text{as } N \to \infty.$$

Using p*, we have

$$S(p^*,N,m) = m/(Ne) \qquad \text{as } N \to \infty. \qquad (2.10)$$

This result agrees with those obtained from the Poisson assumption of station distribution.

Note that the above results are all upper bounds on throughput since for destination stations located at the boundary of two transmission sectors, they will encounter collisions from simultaneous transmission from stations within both sectors. In the analysis, we have assumed the transmission circle to be perfect.

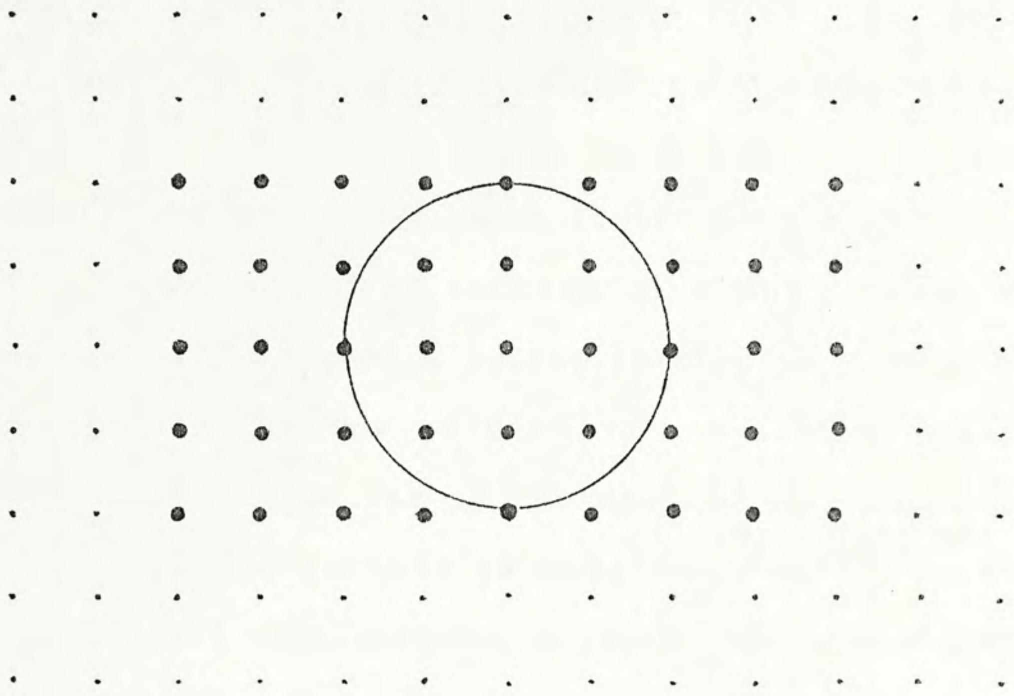

Figure 2.3 The deterministic lattice distribution of stations.

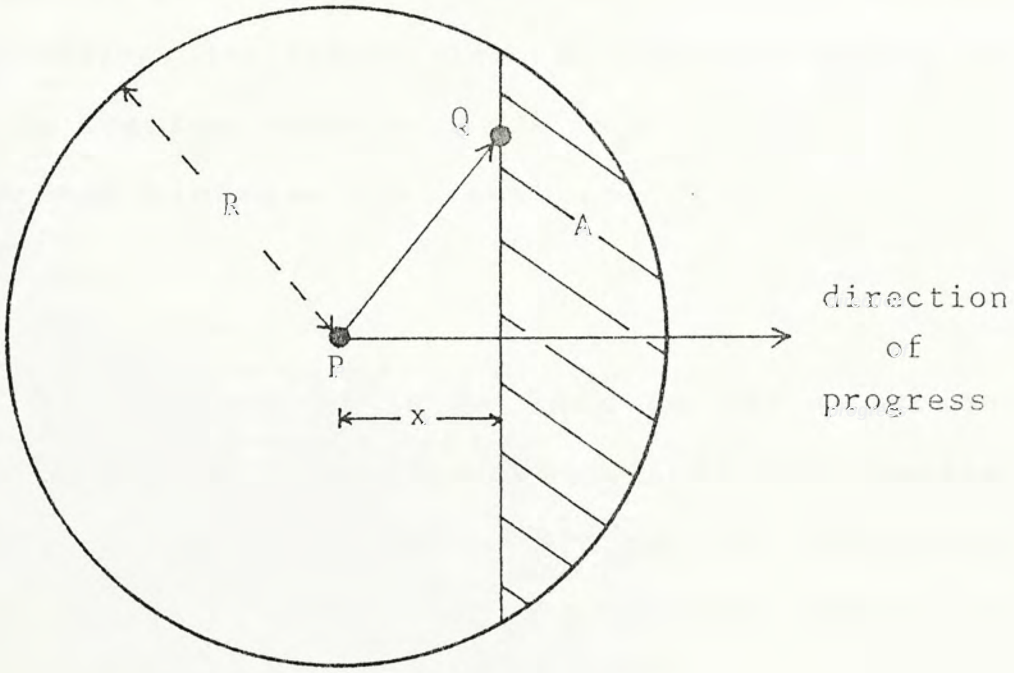

Figure 2.4 The position of the receiver Q (from [14]).

2.3 The Expected Progress of SA/MDA

One main design of multihop packet radio networks is to find the optimal transmission power for each station in the network. A lower transmission power causes fewer interference with other stations and leads to more successful transmission. A higher transmission power can send a packet farther in a single hop and there is a greater chance of finding a suitable intermediate station for routing a packet in the desired direction. Since the goal of transmitting packets in multihop PRNs is to move them towards their final destinations, a second measure of performance is the expected one-hop progress of a packet in the desired direction [11].

To evaluate the expected progress, we adopt the Most Forward within R (MFR) routing strategy [14]. If there are no terminals in the forward direction, the transmitter will send the packet to the least backward station. Note that MFR is a myoptic routing strategy and may not minimize the remaining distance to the destination.

Similar to [14], $Z(p,N,m)$ is defined as the expected progress of a packet in the direction of its final destination per slot from a station according to the MFR routing. Using the techniques given in [14], we derive in a similar manner as follows:

Let z be the progress of a packet per transmission (slot). Consider the situation in Figure 2.4, where P is transmitting a packet to a station on the x-axis outside the transmission circle. Then

$$\text{Prob}[z <= x] = \text{Prob}[\text{no station in the area } A]$$

$$= e^{-(N/\pi)q(x/R)} \qquad (2.11)$$

where

$$q(t) = \cos^{-1}(t) - t\sqrt{1-t^2} \quad . \qquad (2.12)$$

Therefore, we have

$$Z(p,N,m) = \text{Prob}[P \text{ transmits}]\cdot\text{Prob}[\text{the transmission from } P \text{ to } Q \text{ is successful}]\cdot E[\text{progress of a packet}]$$

$$= p\cdot\text{Prob}[B]\cdot\int_{-R}^{R} x\cdot\text{Prob}[x < z <= x+dx]$$

$$= p(1-p)e^{-pN/m}\sqrt{\frac{N}{\lambda\pi}}\,[1+e^{-N}-\int_{-1}^{1} e^{-(N/\pi)q(t)}dt]. \qquad (2.13)$$

Note that, given N and m, Z(p,N,m) is also maximized by the same p* in (2.4), and the normalized maximum is

$$Z(p^*,N,m)\sqrt{\lambda} = \frac{m}{2m+\sqrt{N^2+4m^2}}\exp(-\frac{2N}{(N+2m)+\sqrt{N^2+4m^2}})$$

$$\cdot\sqrt{\frac{N}{\pi}}\,[1+e^{-N}-\int_{-1}^{1} e^{-(N/\pi)q(t)}dt] \quad . \qquad (2.14)$$

When $m=1$, (2.14) is reduced to that given in [14]. Interestingly, we found

$$\frac{Z(p,N,m)}{Z(p,N,1)} = \frac{S(p,N,m)}{S(p,N,1)} = r(m) \ . \qquad (2.15)$$

The functions $S(p^*,N,m)$ and $Z(p^*,N,m)\sqrt{\lambda}$ are plotted against N for several values of m in Figure 2.5 - 2.7. When $m=1$, $Z(p^*,N,m)\sqrt{\lambda}$ has its maximum at $N^*=7.7$, in agreement with [14]. When $m=4$, $N^*=13$. In terms of transmission radius, we have $R^*\big|_{m=4} = \sqrt{13/(\lambda\pi)}$. The associated optimal values are

$$p^* = 0.22$$
$$S^* = 0.084$$
$$Z^*\sqrt{\lambda} = 0.13 \qquad .$$

Take $\lambda = 10$ stations per square kilometer, the optimum radius of the transmission circle with four directional transmitting antennas is 643 meters.

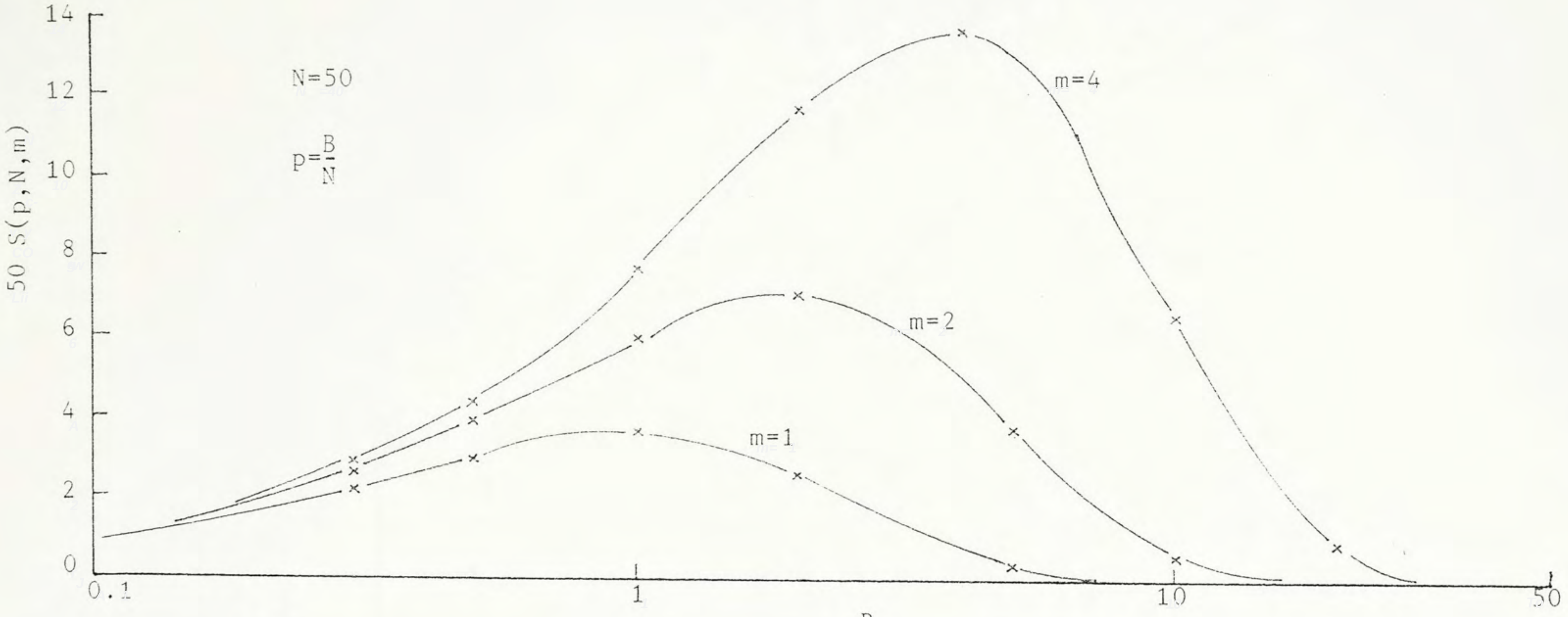

Figure 2.5 The one-hop throughput for SA/MDA.

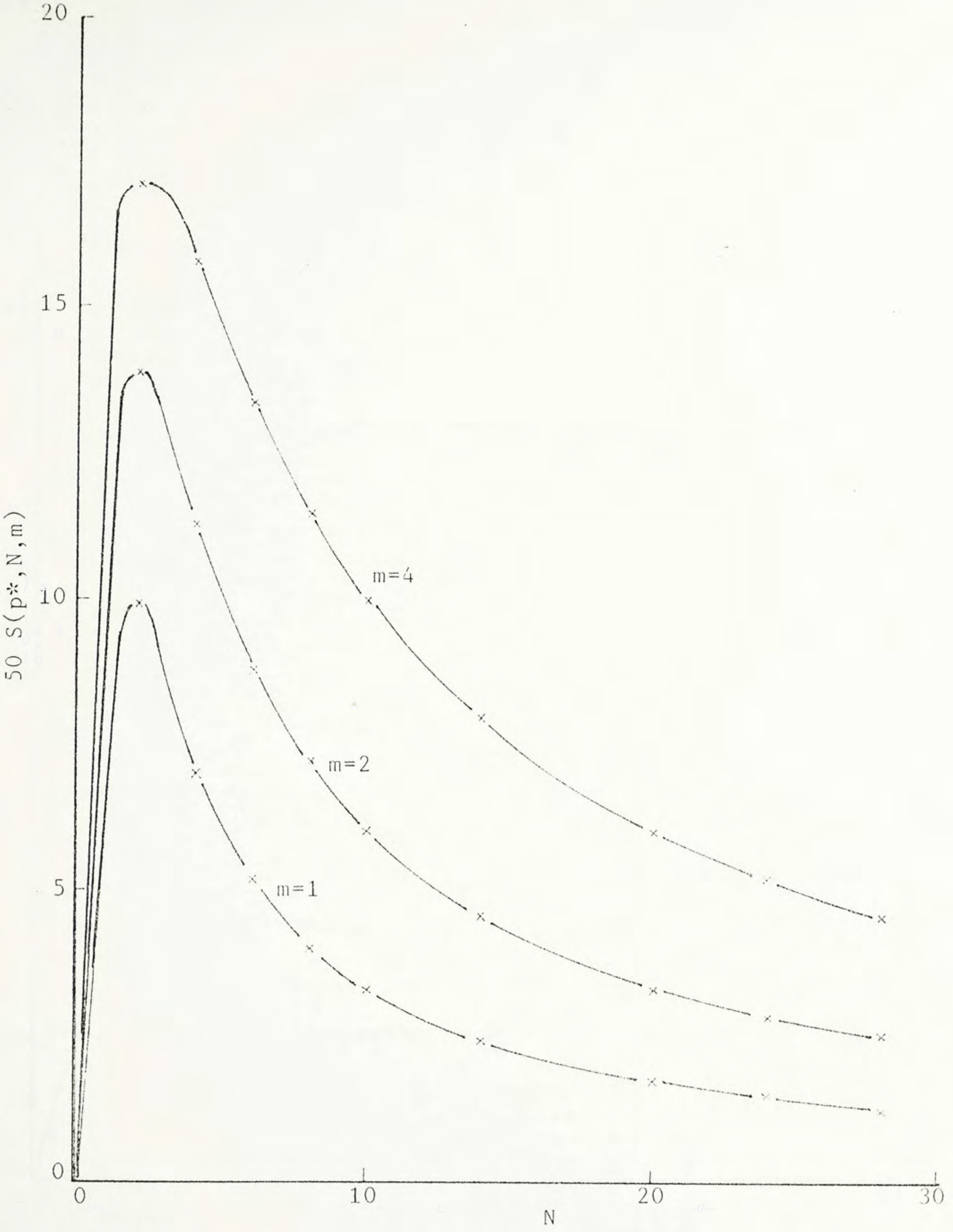

Figure 2.6 The maximum one-hop throughput for SA/MDA.

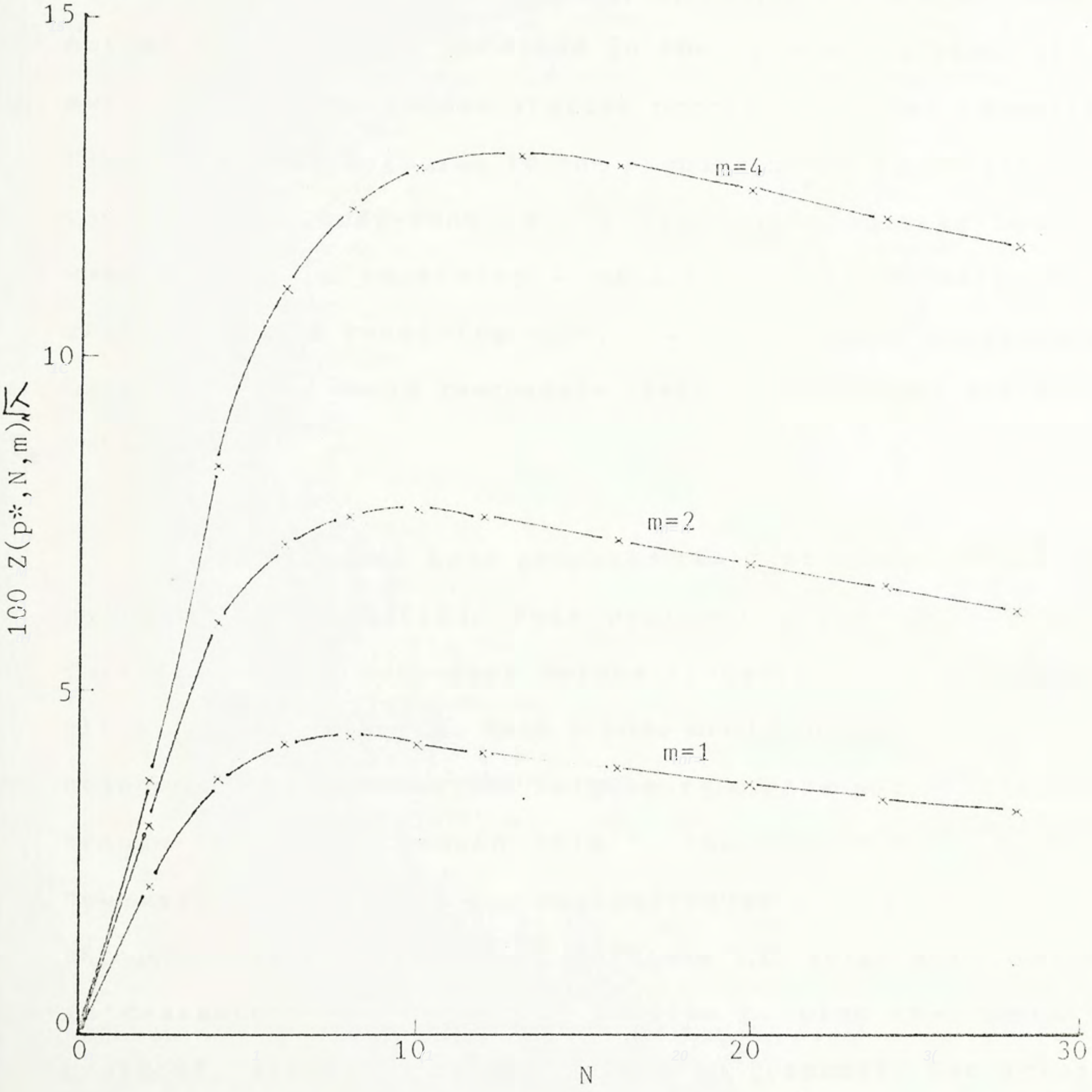

Figure 2.7 The normalized maximum expected progress for SA/MDA.

CHAPTER 3

THE MULTI-TONE MULTIPLE ACCESS PROTOCOL WITH COLLISION DETECTION

It has been shown that for multihop packet radio networks CSMA performs better than ALOHA [7-8, 14], but the improvement is not as large as that obtained in the single-hop case. This is mainly due to the hidden station problem inherent to multihop PRNs. A better solution to the problem could be obtained with the use of a busy-tone [4]. A station broadcasts busy-tone whenever it is receiving a packet. Then the neighbouring stations of the receiving node, when sensing the presence of a busy-tone (BT), would reschedule their transmissions and avoid a collision.

Roy and Saadawi have proposed the CSMA/BT-CD protocol for multihop PRNs [15][16]. This protocol would sense both the carrier and the busy-tone before transmission. According to [16], " a transmission from a node would be successful if the neighbours as well as the neighbours of the neighbours of the transmitting node remain idle ". The use of this protocol, however, would reduce the spatial-reuse effect and lower the throughput as is illustrated in Figure 3.1. Here, when station A is transmitting a packet to station B, with the CSMA/BT-CD protocol, station C is prohibited to transmit. But actually station C could send packets to station D without interfering station B. In the protocol we propose in the following section, stations only sense the busy-tone not the carrier for determining transmission.

In multihop PRNs using multiple directional transmitting antennas, CSMA is not a suitable protocol. Consider the situation in Figure 3.2, station A is transmitting packets to station B using antenna 1. Station D can use antenna 2 to transmit packets to station E simultaneously without interfering B's reception. However station D senses the presence of carrier and inhibits the transmission if CSMA is adopted. On the other hand C senses no carrier and may transmit a packet to B using antenna 1. Thus collision would occur and the throughput is reduced.

In this chapter, the system requirement and the direction table outlined in Chapter 2 still holds. We first propose a new protocol termed as Multi-Tone multiple access with Collision Detection using Multiple Directional Antennas (MTCD/MDA). We then verify the protocol and discuss the "boundary" problem and its solution. Finally we introduce an acknowledging scheme suitable for the MTCD/MDA protocol.

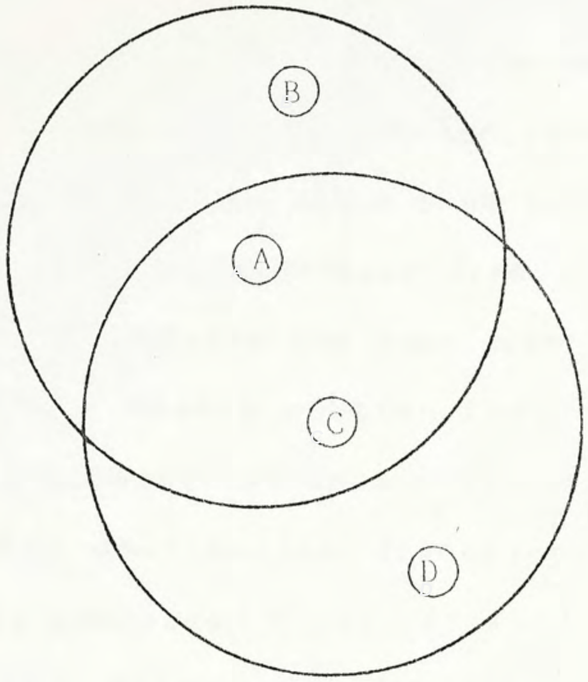

Figure 3.1 Spatial-reuse of omnidirectional antenna.

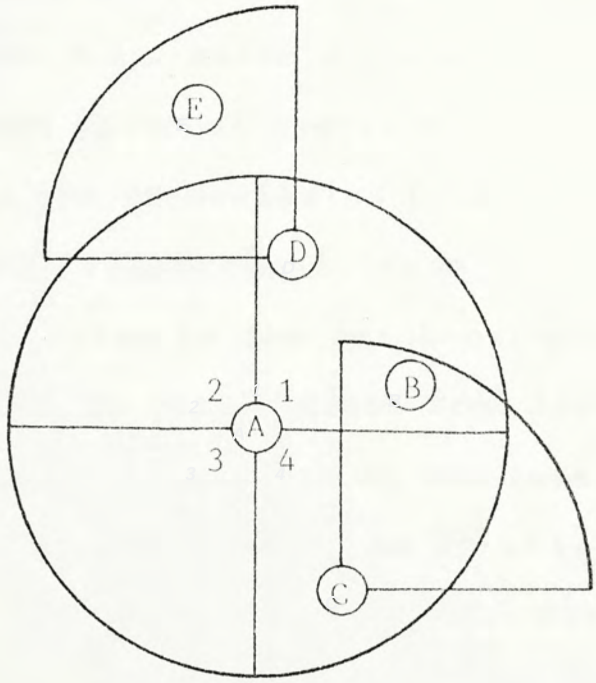

Figure 3.2 Spatial-reuse of directional antenna.

3.1 The MTCD/MDA Protocol

To describe the MTCD/MDA protocol, we use, as an example the four directional antennas per station case. It will be clear later that generalization to other even numbers of antenna cases is trivial. For stations with four directional antennas, four tones are needed to indicate the four directions. The main idea of MTCD/MDA is that when a station transmits a packet to the destination, the transmitter uses only the directional antenna correspond to the destination direction. When the receiver detects a packet addressed to it, it will broadcast different busy-tones to its neighbours. When a ready station detects busy-tones, it will refrain from transmitting packets to the directions from which the busy-tones are coming.

Consider the case where station A is transmitting a packet to station B (Figure 3.3). Since A knows that B is at its 4th quadrant, it uses AT4 (antenna number 4) for sending the packet to B. When B detects the transmission from A, it will broadcast the four busy-tones respectively from its four directional antennas. When a station in the neighbourhood of B detects a busy-tone, say tone k, it will refrain from transmitting packets to the opposite quadrant indicated by the tone. To illustrate, station C receives tone-1 from B; so it will not use AT3 for transmission as long as tone-1 is present. Station C, however, is free to use the other three antennas for transmission since they do not interfere with the transmission from A to B. By this frequency reuse principle, the MTCD/MDA protocol allows

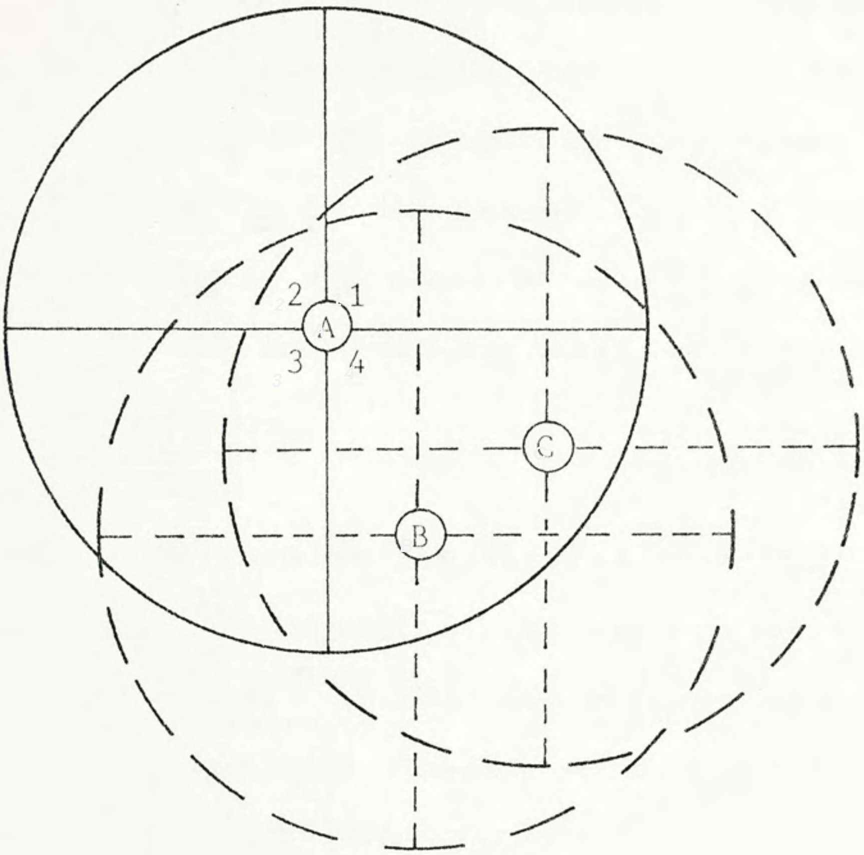

Figure 3.3 Saptial-reuse of MTCD/MDA.

simultaneous transmission without the increase of packet collision.

Since collision still occurs in MTCD/MDA, we need some method to detect collision and stop wasteful transmissions as soon as possible. When A begins to send a packet to B, A should detect the busy-tone from B's direction after some propagation and processing delay T_{CD} if the transmission is successful. If the corresponding tone is not received after T_{CD} seconds, A knows that its packet is not received successfully by B and it stops transmission immediately.

Sometimes A may receive the desired busy-tone even though collision has actually occured on its packet (see (3) below on how this might happen). If that happens, B will detect the collision from the error checks on the packet and stop broadcasting busy-tones immediately. Thus when A loses the expected busy-tone during transmission, it aborts transmission immediately and retries at a later time.

In MTCD/MDA, collision will occur in the following situations:

(1) If an idle station receives two or more transmission simultaneously from its neighbours.

(2) When the destination is transmitting a packet to some other stations or the destination lies within the broadcasting

area of other transmitting stations. To illustrate, consider the situation shown in Figure 3.4. Here A is transmitting a packet to B. Although C knows it cannot use AT3 for transmission, C may use AT2 to transmit a packet to D. Since D lies within the broadcasting area of A, collision occurs at D. Moreover if C uses AT2 to transmit a packet to A, that packet will not be received by A. Station A's transmission, however, is not interrupted.

For collisions caused by (1) and (2), the intended receiver cannot receive the packet. Hence no busy-tone is generated and "collision" condition can be declared at the transmitting station after T_{cd} seconds.

(3) Due to propagation delay, a station may initiate a transmission before receiving i) an ongoing packet destined for it or ii) busy-tones from other receivers. Collision will occur. To illustrate, consider Figure 3.5 where A is transmitting a packet to B. If station E initiates a transmission to B's direction before receiving busy-tone from B, there will be a collision at B due to A and E. Both A and E can detect such collision from an abrupt lose of the busy-tone from B.

Other abnormalities not mentioned will be taken care of by a higher level acknowledgement scheme to be described in section 3.4.

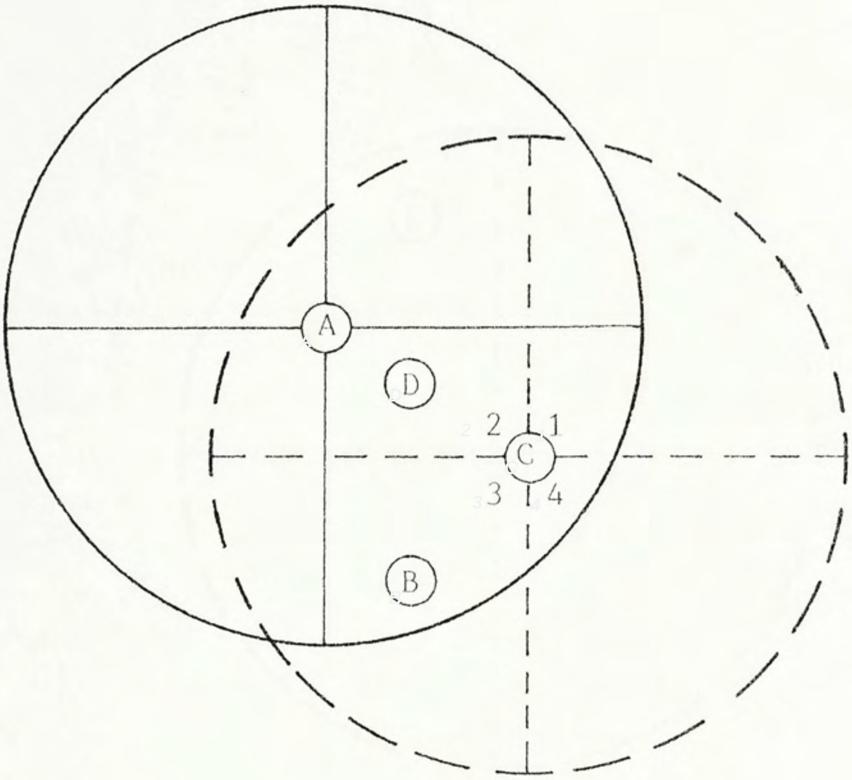

Figure 3.4 Collision situation in MTCD/MDA.

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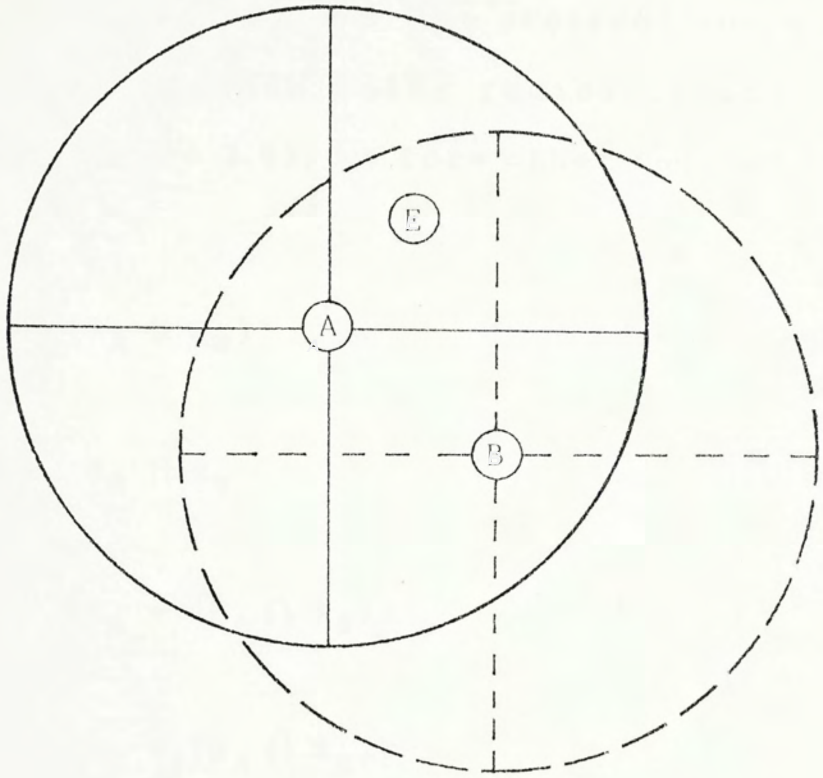

Figure 3.5 Collision situation in MTCD/MDA.

3.2 Verification of The MTCD/MDA Protocol

To verify the MTCD/MDA protocol, we consider the transmission of a packet from station A to station B. If the activities of the neighbours of A and B do not affect the communication between A and B, the protocol works properly. Let R_A and R_B be the transmission region of stations A and B respectively (Figure 3.6), we form other regions of interest as follows:

$$R_1 = (R_A \cup R_B)'$$

$$R_2 = R_A \cap R_B$$

$$R_3 = (R_A - (R_A \cap R_B))$$ $R_A \setminus R_B$

$$R_4 = (R_B - (R_A \cap R_B)) .$$

First consider R_1. Stations in R_1 are outside the hearing and transmission range of both A and B, so their activities will not affect the communication between A and B. Moreover, since they cannot hear the busy-tones coming from B, they can initiate transmission and their destinations' busy-tones will not be confused with those coming from B. If the stations in region R_1 act as receiver and broadcast busy-tones, their busy-tones cannot reach A.

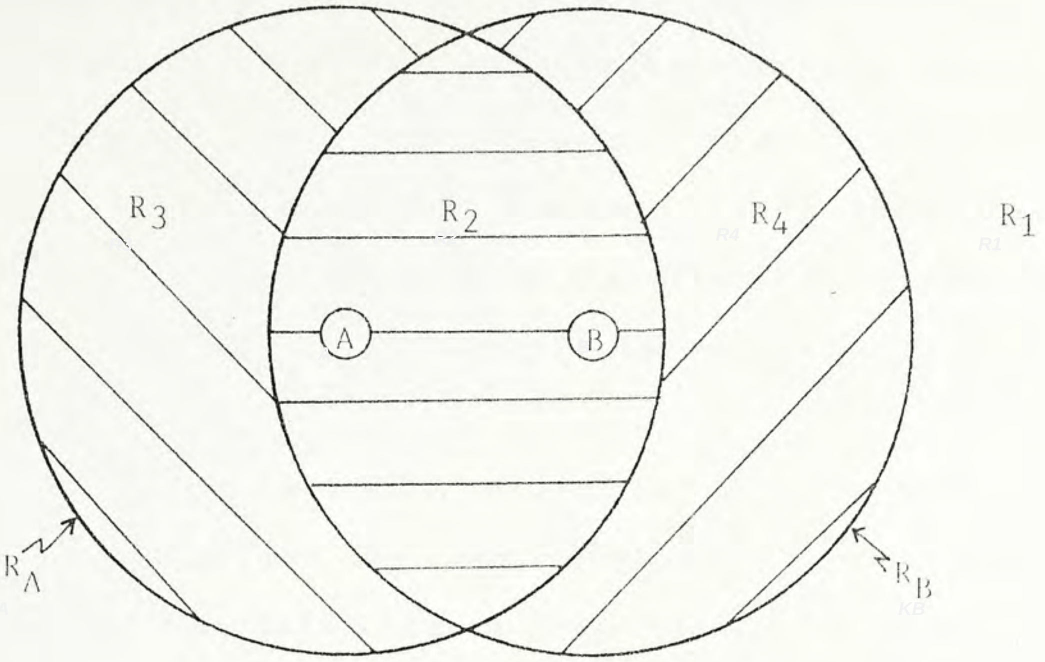

Figure 3.6 Verification of MTCD/MDA.

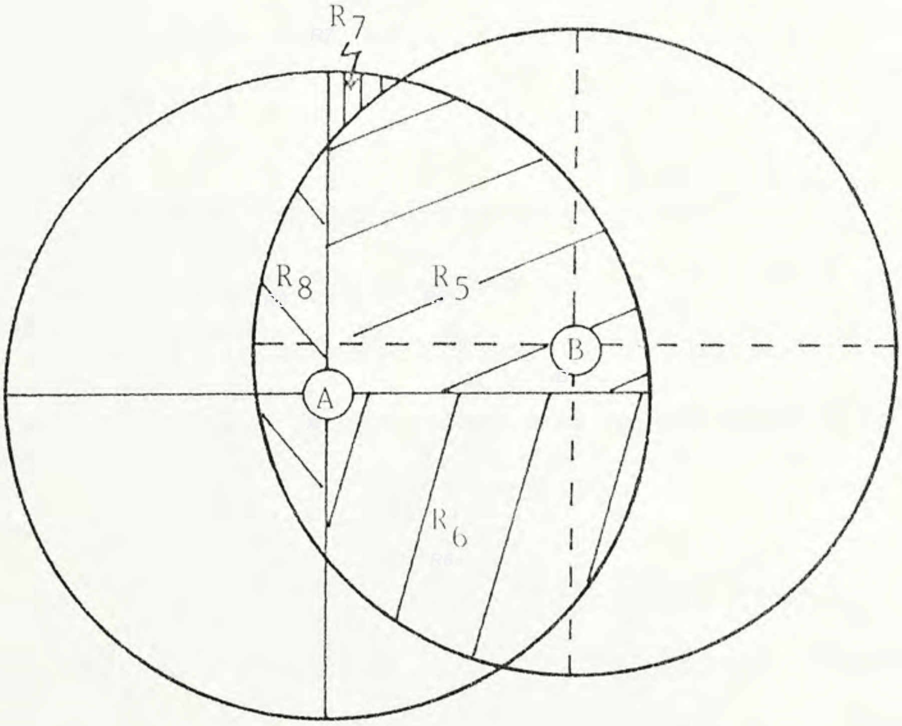

Figure 3.7 Verification of MTCD/MDA.

Next consider R_B. Stations in R_B will receive busy-tones coming from B. Hence they will not use the antennas pointing at B's direction for packets transmission. To detect collisions when using other antennas, stations in R_B should detect busy-tones that are not coming from B's direction. Therefore B's busy-tones will not affect their collision detection process.

Next, we prove that the activities of the stations in $R_B \cup R_7$ will not affect the communication between A and B. We shall divide $R_B \cup R_7$ into three subregions: R_4, $R_5 \cup R_7$, $R_6 \cup R_8$ (see Figure 3.7) and prove that the above is true for all three regions.

i) If there are packets successfully reaching the stations in region R_4, these stations will broadcast busy-tones. Since they are outside the hearing range of A, their busy-tones would not affect A.

ii) Packcts sending to stations (excluding B) in $R_5 \cup R_7$ will encounter collisions since B is in the same region and is receiving a transmission from A. These stations therefore will not broadcast busy-tones and hence they will not affect the communication between A and B.

iii) If stations in $R_6 \cup R_8$ are receiving successful transmissions and broadcasting busy-tones, their busy-tones reaching A will be different from B's busy-tone. Hence A will not get confused.

Lastly, consider R_3. Stations in R_3 are outside the hearing range of B; hence their transmission will not affect B in receiving A's transmission. If the intended destination of a particular station in R_3 is within the broadcasting area of A, there will be a collision. The intended destination therefore will not generate a busy-tone. Since the transmitting station cannot hear B's busy-tone, they can detect such collisions unambiguously. If a station in $R_3 - R_7$ (i.e. R_3 but excluding R_7) receives a successful transmission and broadcasts busy-tones, A will hear their busy-tones. However, their busy-tones are coming from quadrants other than that of B's busy-tone. By distinguishing the busy-tones, A will not get confused.

To summarize, we have verified that while A is transmitting a packet to B and B replies with busy-tones, the activities of the neighbours of A and B will not affect the communication between A and B. In addition, collision detection by the neighbours of A and B is not affected by the communication between A and B. Hence the correctness of the MTCD/MDA protocol is verified.

3.3 The Boundary Problem and its Solution

In the preceding section, we have assumed that the transmission circle is perfect. It means that signals from each station cannot reach the stations outside its transmission circle and it cannot receive any signal coming from stations outside the transmission circle. Under this condition, the MTCD/MDA protocol works well. However, in real situation, the transmission circle is seldom perfect, and the boundary problem appears.

Consider the situation in Figure 3.8, where station A has a packet sending to B and station C has a packet sending to D. If they initiate the transmission almost at the same time, there will be a collision at B but D will receive the transmission from C successfully. If the transmission circle is perfect, there will be no problem because A cannot hear D's busy-tone which is acknowledging C. But D could be just outside the transmission circle of A and there is a chance that A will hear D's busy-tone and mistakenly regards it as B's acknowledging busy-tone. Such problems can be solved by any ARQ (Automatic Repeat Request) schemes [23]. The following is an alternate solution. We first note that if A can hear D's tone, D can also hear A's transmission. We could require S_p, the power of the weaker signal from A be less than a fixed value x before D declares no collision. If S_p is larger than the fixed value x, D will treat it as collision and does not broadcast busy-tone. Hence the above "false" busy-tone problem is avoided.

Besides the boundary case on the transmission circle, there are also boundary cases in the division of antenna broadcasting regions. In the preceding discussion, we have assumed that the transmission region of the directional antenna is a perfect sector of a circle. If a station is located on the boundary of two sectors of another station, it can receive signals from two antennas and problems will arise. To illustrate, consider the situation in Figure 3.9 where stations A and B lie on the axis of the antenna broadcasting boundary. If A wants to send a packet to B, A can choose to use antenna AT3 or AT4 arbitrarily or can allow the decision to depend on the traffic load. If A receives a packet from other stations and broadcasts busy-tones, B will detect both tone-3 and tone-4 from A. Station B therefore will refrain from using AT1 and AT2 so as not to interfere with A's reception. Hence the MTCD/MDA protocol is not affected by having stations at the boundaries of antenna transmission regions.

If the antenna broadcasting region is not clear-cut, which is the usual case, the transmission regions of two adjacent antennas will overlap and forms a narrow sector. Usually directional antennas of broadcasting angle around 100 degree instead of around 90 degree is used to make sure that every neighbour station falls into the broadcasting region of at least one antenna (Fugure 3.10). We now illustrate that the validity of the MTCD/MDA protocol is not affected by this overlapping of transmission regions. Consider the example in Figure 3.11, if A

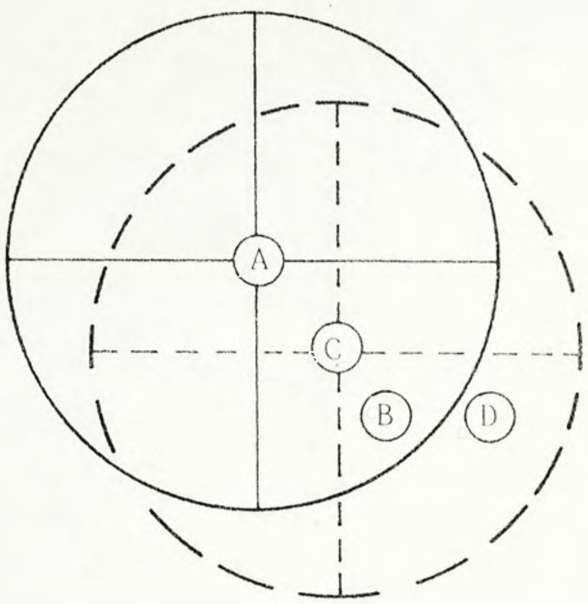

Figure 3.8 The boundary case of transmission circle.

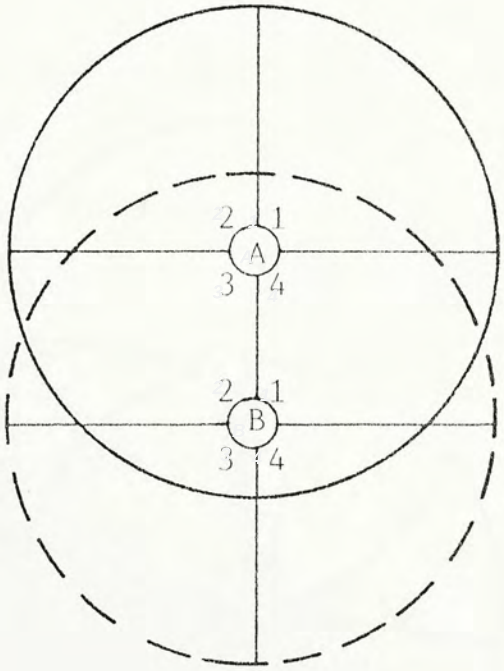

Figure 3.9 The boundary case of antenna broadcasting region.

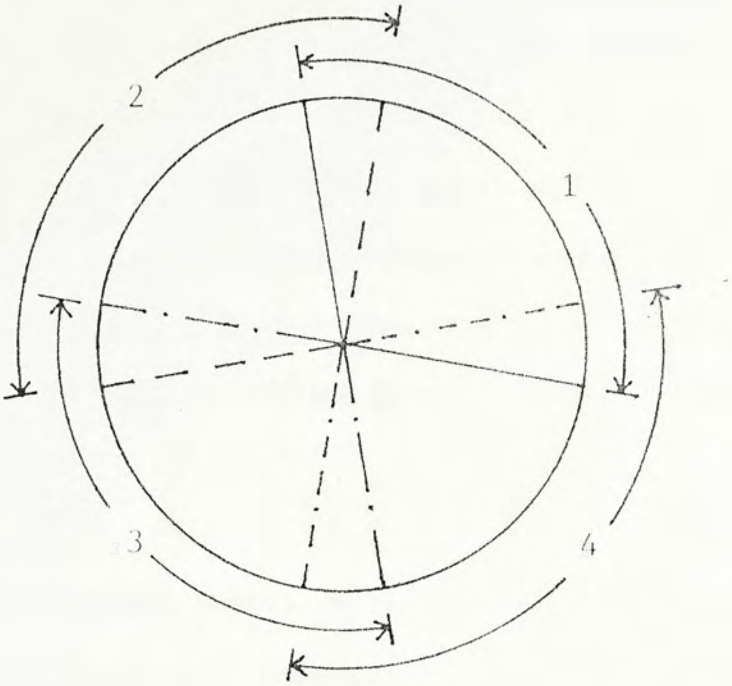

Figure 3.10 Overlapped area of antenna broadcasting region.

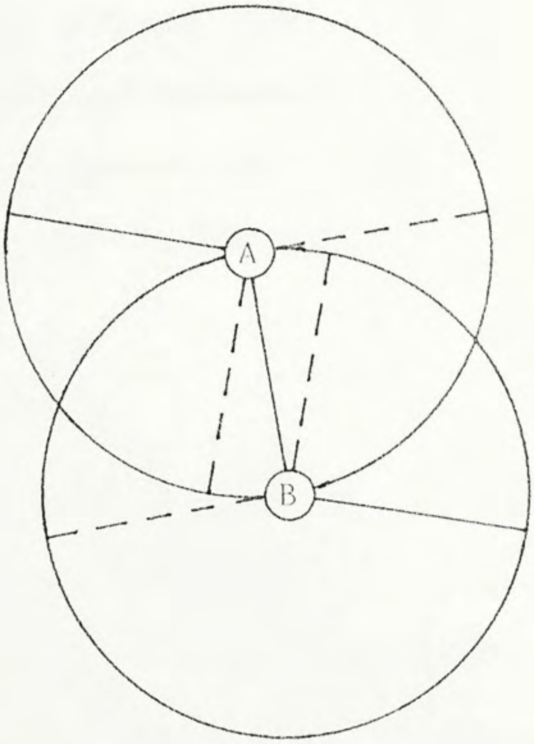

Figure 3.11 MTCD/MDA in overlapped area.

has a packet for B, A will use antenna AT4 for transmission. When B receives the packet and broadcasts busy-tones, A will detect both tone-1 and tone-2. Tone-2 is for collision detection purpose; whereas tone-1 will prohibit A to use AT3 for transmission (if simultaneous transmission by one station is possible), as this will interfere with the reception at B. This prohibition of transmission is just what the MTCD/MDA protocol desired.

The above protocol works only for even number of directional antennas, since for odd number of antennas, the concept of "opposite quadrant" is not define. As will be shown in the next chapter, the more the number of antennas, the higher the throughput. But this is at the expense of a more complex system and more expensive antennas: for forming beams of desired pattern. We propose a four directional antennas per station system to be a compromise between performance and cost, although a two antenna/station system also works and provides substantiate throughput gain compared to the one antenna/station system.

3.4 The Extended Busy-Tone Acknowledgement (EB/ACK)

There are two main sources of error in multiacess radio channels. The first is the random noise on the radio channel and the second is the multiuser interference in the form of overlapping packets. For multihop PRNs using omnidirectional transmitting antennas, a station can know whether or not its neighbour has received a packet correctly by just listening to the retransmission. This eliminates the need for explicit acknowledgement. However, some kind of acknowledgement is still needed at the last hop, because the final destination does not retransmit its input.

For directional antenna transmission, this kind of echo acknowledgement cannot be used since not all the neighbours of a station can hear the transmission. To ensure the integrity of the transmitted data, we propose in the following the use of an error detecting code in conjuction with a hop-level positive acknowledgement of each correctly received packet.

If ACK (acknowledgement) packets are transmitted back to the originating station on the same channel, channel throughput will be reduced due to more interference between data and ACK packets. For CSMA channels with omnidirectional transmitting antennas, we can give priority to ACK packets by the following operation [22]:

(1) A ready station can transmit its packet only if the channel is sensed idle for more than "a" seconds (a is the propagation delay).

(2) All acknowledgement packets are transmitted immediately without incurring the "a" seconds delay.

This type of acknowledging scheme does not work for directional antenna systems because transmission is to a particular direction. Hence a station cannot be sure if its neighbour is transmitting by just listening to the channel.

We now propose an acknowledging scheme suitable for the MTCD/MDA protocol in multihop PRNs with directional antennas. The main idea is to extend the duration of busy-tone for acknowledgement purpose. No explicit ACK packet is required and the busy-tone acts as an implicit acknowledgement.

The Extended Busy-tone implicit Acknowledgement scheme (EB/ACK) works as follows:

(1) After receiving a packet completely, the receiver continues to transmit the busy-tone and examines the error detecting block code. Only the particular tone to the transmitting station is needed for acknowledgement. The other three tones need not be sent.

(2) If error is detected, the receiver stops transmitting the busy-tone immediately. If no error is detected, the

receiver continues transmitting the busy-tone for an interval just long enough for the acknowledgement purpose.

(3) At the transmitting side, right after it has completed its packet transmission, it starts to time the busy-tone.

(4) If the busy-tone duration is shorter than expected, the sender declares the packet transmission unsuccessful and will retransmit at a later time. If the busy-tone lasts longer than expected, two or more busy-tones are overlapped. The sender therefore declares collision and retransmits the packet later. Otherwise, the packet is assumed to be correctly received.

3.5 Summary of MTCD/MDA-EB/ACK

Due to the propagation delay of busy-tone, it is better to adopt a slotted version of MTCD/MDA. Time is divided into slots of equal duration (minislot) of size a, where a must be larger than the roundtrip propagation delay from a station to its farthest neighbour (i.e. R meters away). Each station is required to start the transmission of its packets at the beginning of the slot only. Like CSMA, according to the action a station takes after sensing the busy-tone, we have the nonpersistent and the p-persistent versions of the slotted MTCD/MDA. We now summarize the slotted nonpersistent MTCD/MDA-EB/ACK protocol as follows:

(A) Transmission Protocol

(1) When a station has a packet ready to send, it searches the direction table to decide which directional antenna is to be used.

(2) The ready station then senses the busy-tone of the opposite quadrant at the beginning of the next slot. If busy-tone is detected, the station schedules the packet transmission to some later time according to the retransmission delay distribution. At this new point in time, it senses the expected busy-tone again and repeats the algoritnm described.

(3) If no expected busy-tone is detected, the station transmits its packet.

(4) After the station has started the transmission, if the expected busy-tone is not detected after T_{CD} seconds or if the expected busy-tone is lost during transmission, the station stops transmission immediately and schedules the retransmission of the packet to some later time.

(5) After the station has finished the transmission, if the extended busy-tone is lost before the timeout T_{ACK1} or if the extended busy tone lasts longer than T_{ACK2} seconds, the station will retransmit the packet later. If the duration of the extended busy-tone falls between T_{ACK1} and T_{ACK2}, the packet is assumed to be correctly received.

(B) Reception Protocol

(1) When an idling station detects a packet sending to it, it broadcasts different busy-tones by the four directional antennas immediately.

(2) As soon as the station detects a collision or error in the packet while it is receiving a packet, it stops broadcasting the busy-tones.

(3) After the whole packet has received, the station continues broadcasting the particular busy-tone to the transmitting station and examines the error detecting block code. If the packet has error, the station stops broadcasting the busy-tone immediately. Otherwise, the station continues broadcasting the busy-tone for T_{ACK2} seconds to acknowledge the transmitting station.

CHAPTER 4

THE PERFORMANCE OF MTCD/MDA

The MTCD/MDA protocol, being more complex, should give a better throughput performance than the SA/MDA protocol. In this chapter, we shall first derive the one-hop throughput and the expected progress for the slotted nonpersistent MTCD/MDA. We then present numerical results and compare the throughput and progress performance to SA/MDA.

4.1 The Analysis

Most of the assumptions we use here are the same as those in Chapter 2. These assumptions include the Poisson distribution of stations with average density λ, transmission radius R, MFR (most forward within R) routing and $N \triangleq \lambda \pi R^2$. In addition, let the time axis be slotted into equal intervals (minislots) of size a, where a must be larger than the round trip propagation delay from a station to its farthest neighbour (i.e. R meters away). Let the packet length be fixed and be equal to τ minislots. The number of transsmitting antennas/station m can be one or any even number.

Define the one-hop throughput S as the average number of successsful packet transsmissions in τ minislots from a station. The channel is assumed to be noiseless, hence no extended busy-tones are required. The one minislot overhead for acknowledgement is therefore ignored in our analysis. It is easy to generalize the analysis to the noisy channel case:

$$S\Big|_{\text{noisy channel}} = S\Big|_{\text{noiseless channel}} \left(\frac{\tau}{\tau+1}\right)(1-P_e) \qquad (4.1)$$

where P_e is the probability of packet error due to random noise.

Whether a station transmits a packet or not as a result of sensing the expected busy-tone in a sequence of slots is assumed to be governed by indepentent Bernoulli trails (A similar assumption is used in [4] and [14]). For every minislot (expect during transmission), each station transmits a packet with probability p.

Consider the transmission of a packet from an arbitrary station P to its neighbouring station Q (Q is a neighbour of P if it is inside P's transmission range). Let p_s be the probability that a station starts a successful transmission in a certain minislot, then

$$S = \tau\, p_s \quad . \qquad (4.2)$$

We observed that the above S is not the long-time average value. The reason for that, as explained in [14] is "we have not taken into account the channel activity cycles (idle and busy) whose duration is variable. Thus, the values obtained may be viewed as giving the instantaneous values at transmisssion start times; note that S and Z in slotted ALOHA cases are overall means and instantaneous values at the same time. Thus the comparsion between CSMA and ALOHA is meaningful". For the same argument, we can compare the performance of MTCD/MDA to SA/MDA with meaningful result.

The probability p_s is evaluated as

$$p_s = \text{Prob[the transmission is successful} \mid \text{P transmits and Q exists]} \cdot \text{Prob[P transmits]} \cdot \text{Prob[there is at least one station within R]}$$

$$= p_s' \, p(1-e^{-N}) \quad . \tag{4.3}$$

We now proceed to find p_s'. Note that

$$p_s' = \text{Prob[Q is not active during a minislot]} \cdot \text{Prob[Q is not within the transmission quadrants of other neighbouring active stations]}$$

$$\triangleq P_1 \cdot P_2 \quad . \tag{4.4}$$

If Q is not active, it must be idling and does not transmit in that minislot, thus

$$P_1 = (1-S)(1-p) \quad . \tag{4.5}$$

To evaluate P_2, let p_a be the probability that a station is active during a minislot, then

$$p_a = S + (1-S)p \quad . \tag{4.6}$$

Note that $P_1 = 1 - p_a$ as expected. Since there are m broadcasting quadrants around a station, the probability that a station is not actively transmitting towards a certain direction can be shown to be equal to $1-p_a/m$ (see Appendix). Hence we have

$$\begin{aligned} P_2 &= \text{Prob[Q is not within the transmission quadrants of other neighbouring active stations]} \\ &= \sum_{i=0}^{\infty} \text{Prob[all i neighbouring stations of Q are not actively transmitting towards Q's direction} \,|\, \text{Q has i neighbours]} \cdot \text{Prob}[A_i] \\ &= \sum_{i=0}^{\infty} (1-p_a/m)^i \left(\frac{N^i}{i!} e^{-N}\right) \\ &= e^{-p_a N/m} \quad . \end{aligned} \tag{4.7}$$

Substitute (4.5) and (4.7) into (4.4) and then (4.3) and (4.2), we have

$$S = \tau p(1-p)(1-S)(1-e^{-N}) \exp[-(S+(1-S)p)N/m] \quad , \qquad (4.8)$$

which can be solved using any standard numerical technique such as the bisection method.

When p tends to one, more and more collisions would occur, therefore the throughput S would tend to zero. From (4.6), we find that p_a will approach towards p. Hence (4.8) is reduced to

$$S = \tau p(1-p)(1-e^{-N})e^{-pN/m} \qquad \text{as } p \to 1. \qquad (4.9)$$

Compared with (2.3), the one-hop throughput of MTCD/MDA is just τ times of SA/MDA as p tends to one. This is expected since as p tends to one, the probability of successful transmission is the same for MTCD/MDA and SA/MDA as busy-tone is seldom generated. Using the MTCD/MDA protocol, if a station does not transmit successfully, it will try again in the next minislot. But, if SA/MDA is used, the station would retransmit the packet after τ minislots. Hence the throughput gain is τ when p tends to one.

We now turn to find Z, the expected progress of a packet in the direction of its final destination per τ minislots from a station according to the MFR routing [14]. Since on the average, there are S successful transmissions every τ minislots, we have

$$Z = S \cdot E[\text{progress of a packet}] \quad . \qquad (4.10)$$

Using the techniques given in [14], we derive in a similar manner that

$$Z\sqrt{\lambda} = S\sqrt{\frac{N}{\pi}}\,[1+e^{-N}-\int_{-1}^{1} e^{-(N/\pi)q(t)}dt] \qquad (4.11)$$

where $\quad q(t) = \cos^{-1}(t)-t\sqrt{1-t^2} \quad .$

Finally, we assume the spatial distribution of stations to be a deterministic lattice and evaluate the one-hop throughput again. Following a similar procedure, we get

$$S = \tau\, p(1-p)(1-S)(1-p_a/m)^{N-2} \qquad N >= 2 \qquad (4.12)$$

for deterministic lattice networks.

Once again all the above results are all upper bounds on throughput and expected progress.

4.2 Numerical Results

In Figure 4.1 to 4.3, we plot the expexted throughput in a circle of radius R (N·S) versus the traffic factor B ($\triangleq p \cdot N$) for various values of τ, m and N. The probability of transmitting a packet p in each case is B/N. Firstly, we observe that the one-hop throughput S gradually increases as p increases. The maximum value of S is attained at p = m/N. This is expected since p = 1/N corresponds to setting the average traffic load to be equal to one packet per minislot within the transmission range. When m directional antennas are used, the average traffic load can be raised m times to m/N to attain the maximum throughput. As p increases, more collisions would occur; and the throughput is reduced. As p tends towards one, S would approach to zero as expected.

Since the statistics of channel contention time is independent of the packet length, a longer packet would leads to a higher throughput. This effect can be observed in Figure 4.1 and 4.2. When the packet length is doubled, the maximum throughput increases by 30 percent. When compared to SA/MDA, the maximum one-hop throughput of MTCD/MDA is about three times of SA/MDA.

In Figure 4.4 to 4.6, the normalized expected progress $Z\sqrt{\lambda}$ is plotted versus N where the optimal probability p=m/N is used. We find that for m=1, the maximum value of Z is obtained when N=7. When four directional antennas are used, the average number of stations included within the transmission range should be 13 to attain the optimal expected progress. It is interesting to point out that the optimal number of stations to be included in the transmission circle is the same as that of SA/MDA.

When compared to CSMA, a typical value of $Z^*\sqrt{\lambda}$ given in [14] is 0.05 for CSMA. This value is obtained when N=5.3 . The optimal value of normalized expected progress for MTCD/MDA with m=1 is 0.143, which is 2.8 times larger than CSMA and is obtained when N=7. When compared to SA/MDA, the optimal expected progress of MTCD/MDA is about three times higher. Whereas CSMA is only about 16 percent better than Slotted ALOHA [14]; hence MTCD/MDA has a better performance than Slotted ALOHA and CSMA.

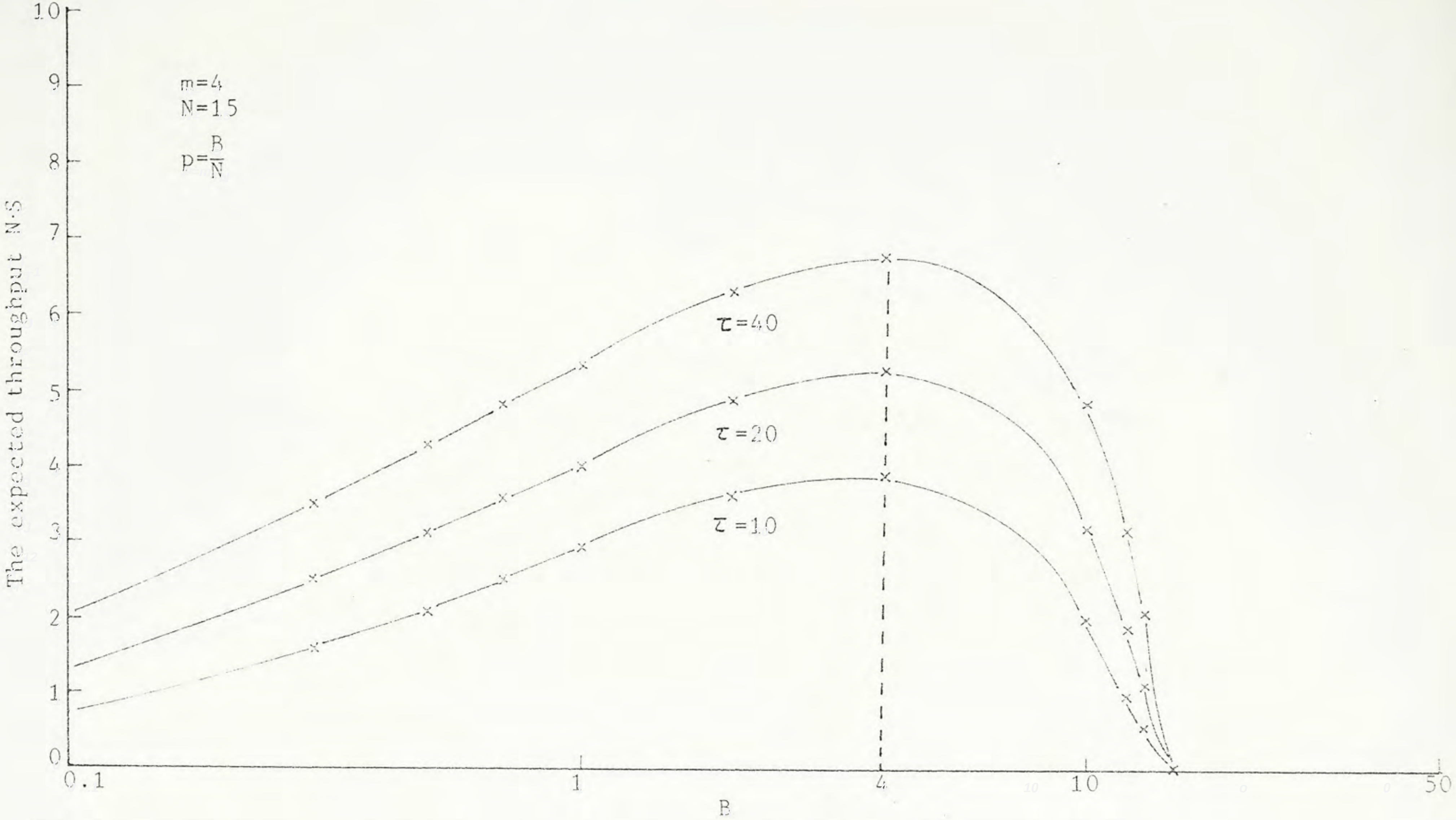

Figure 4.1 The expected throughput versus the traffic factor for MTCD/MDA.

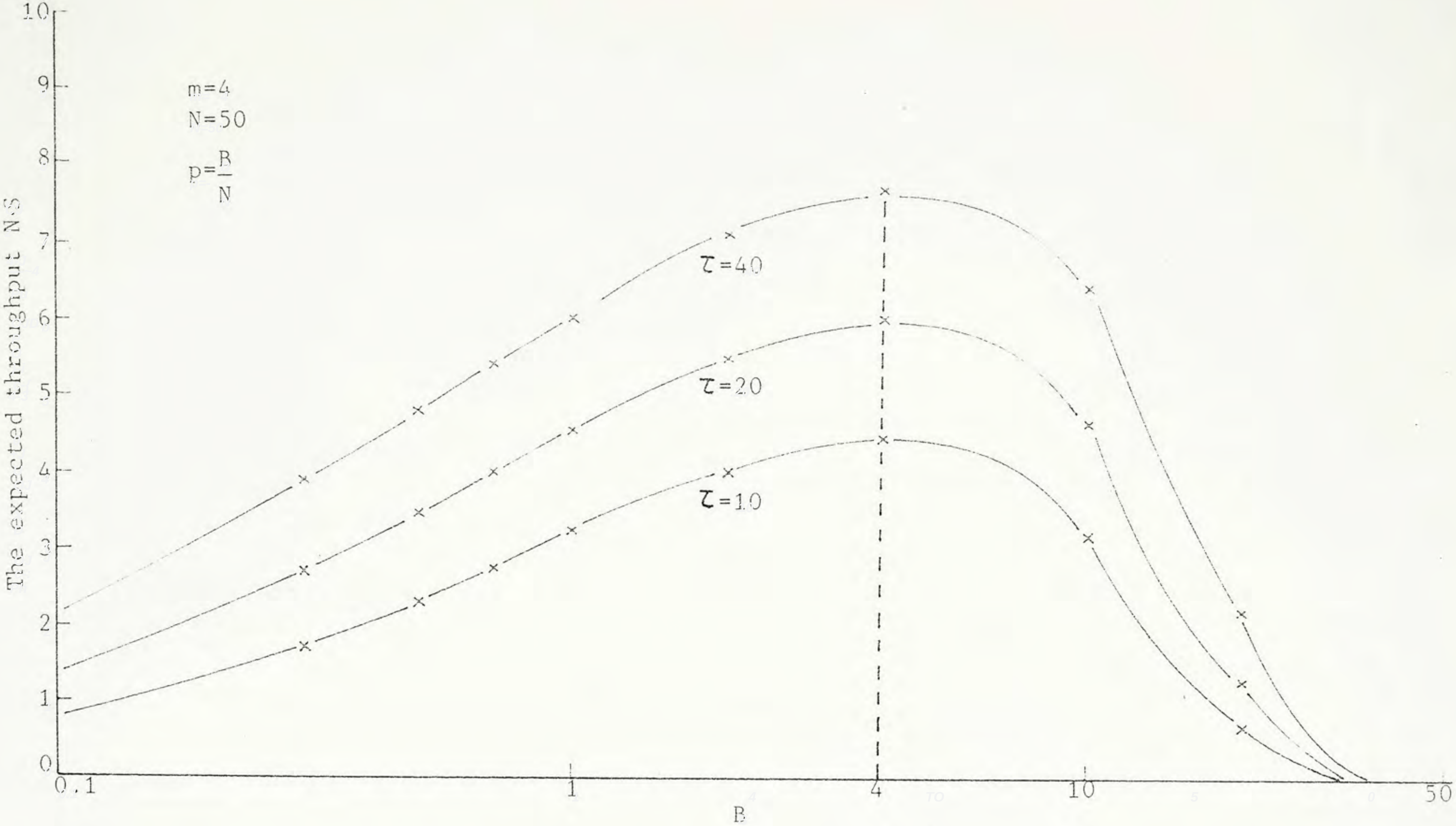

Figure 4.2 The expected throughput versus the traffic factor for MTCD/MDA.

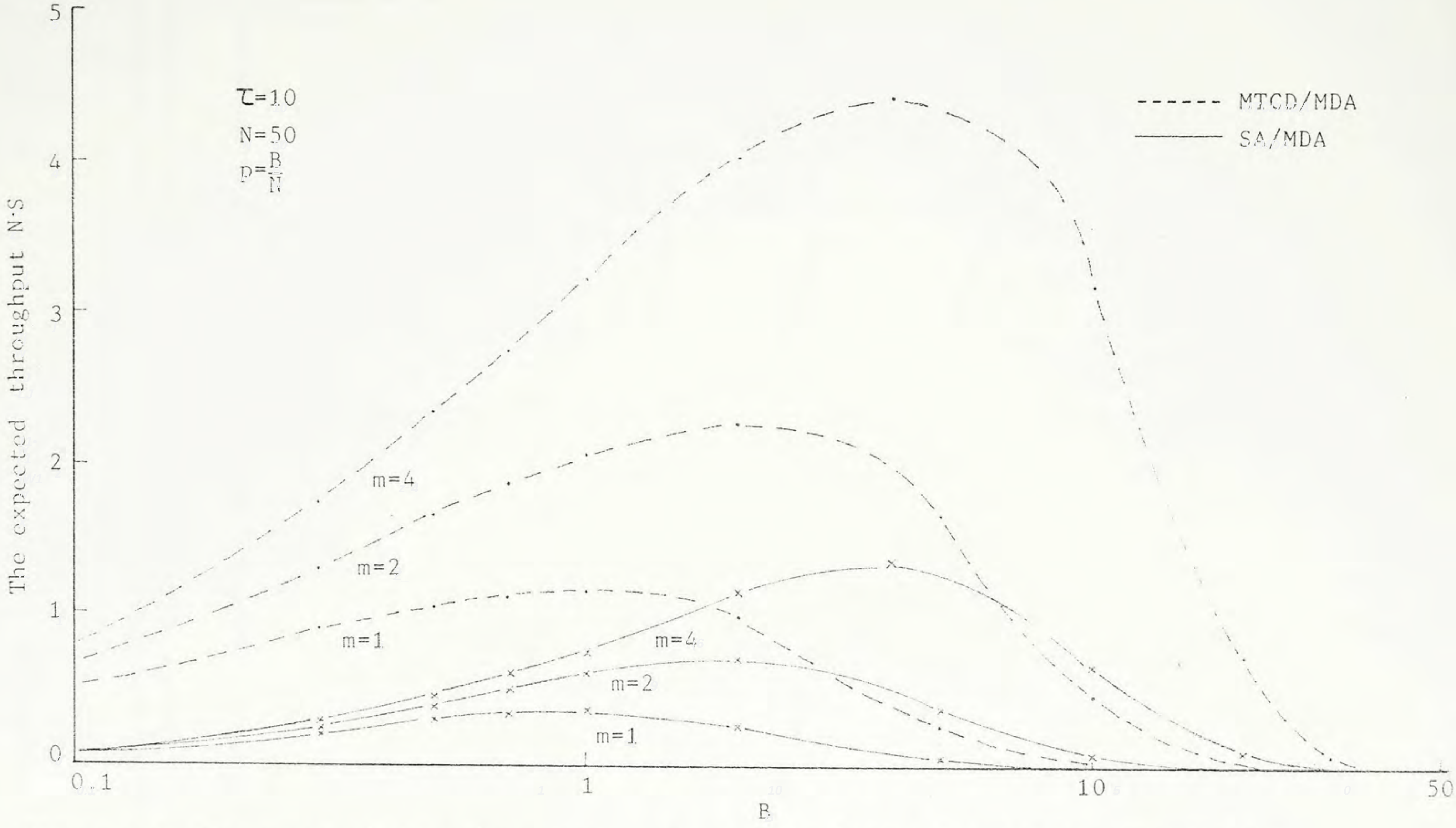

Figure 4.3 The expected throughput versus the traffic factor for SA/MDA and MTCD/MDA.

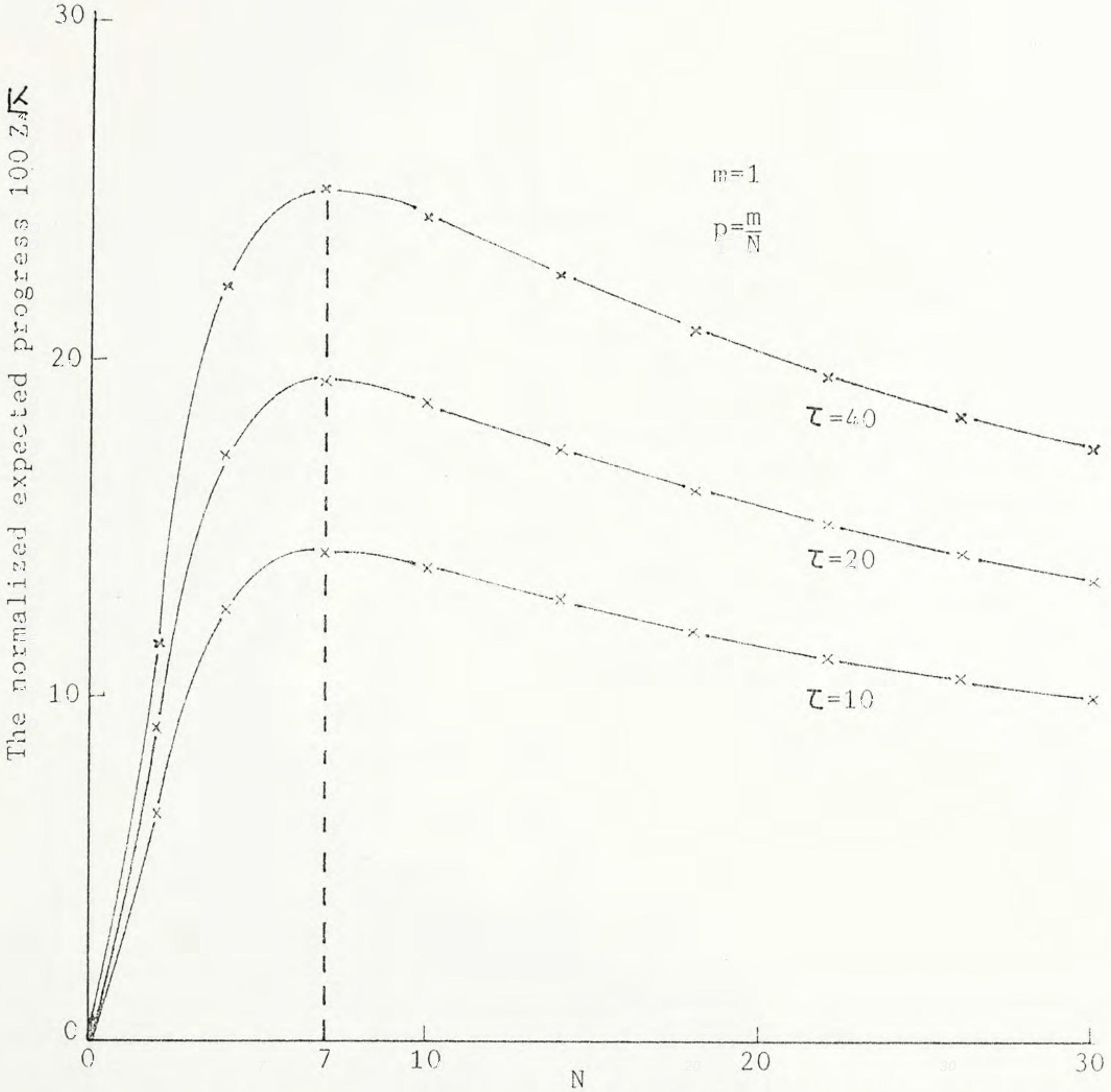

Figure 4.4 The normalized expected progress versus the average number of stations in the transmission circle for MTCD/MDA.

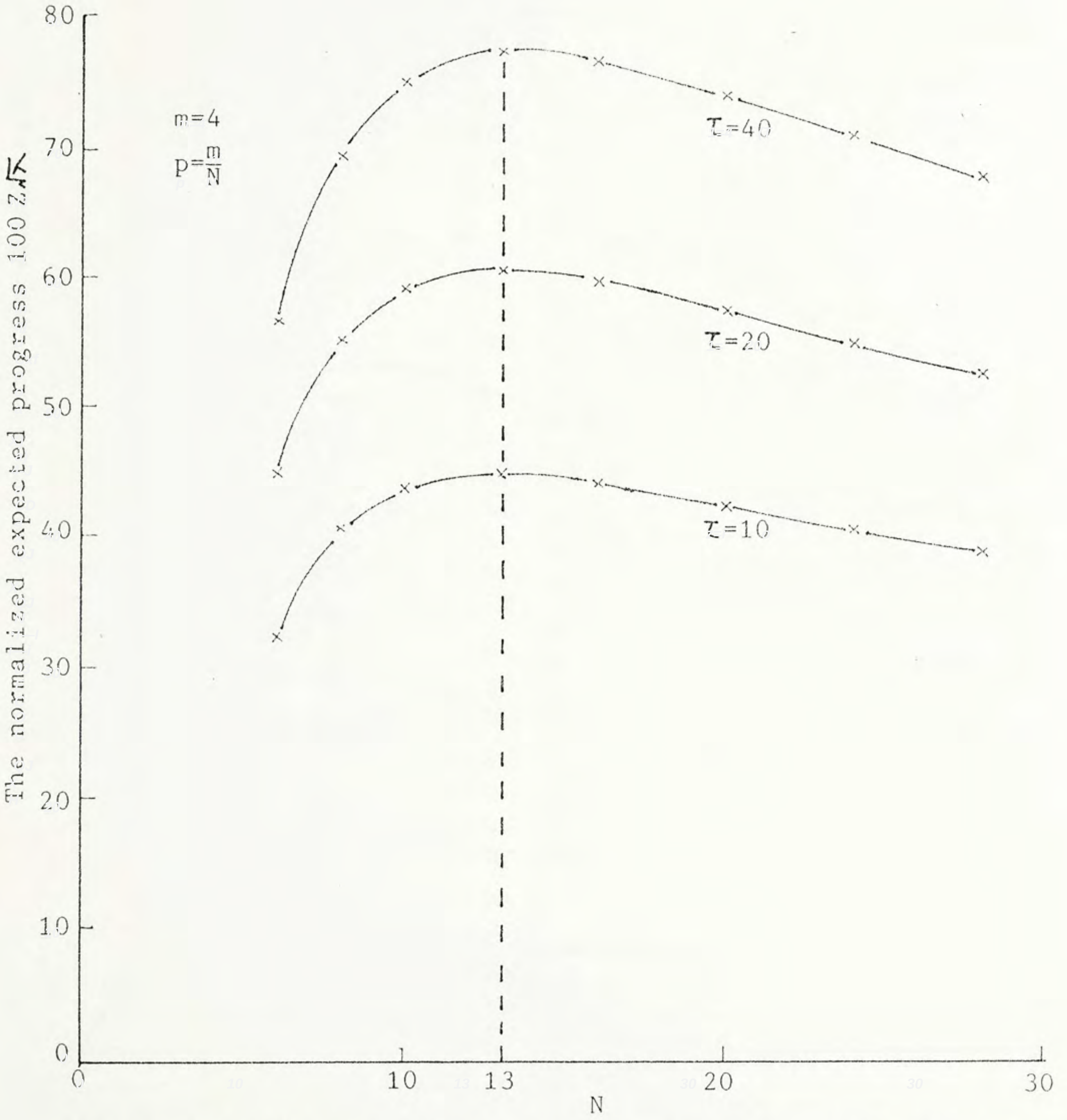

Figure 4.5 The normalized expected progress versus the average number of stations in the transmission circle for MTCD/MDA.

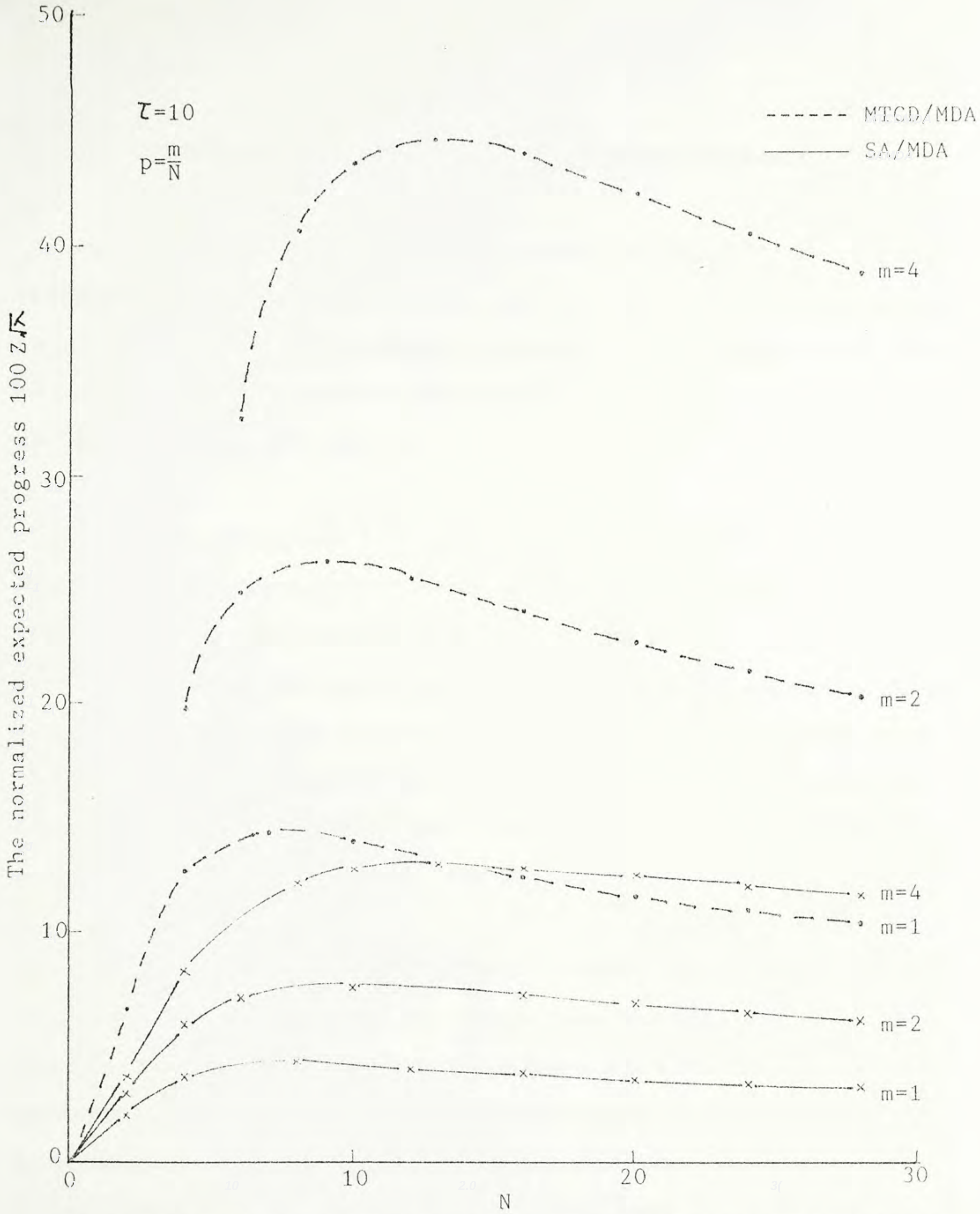

Figure 4.6 The normalized expected progress versus the average number of stations in the transmission circle for SA/MDA and MTCD/MDA.

CHAPTER 5

CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

In this thesis, we have introduced the use of directional transmitting antenna in multihop packet radio networks. We have shown that using directional transmitting antennas has the advantage that the network throughput is increased by a greater spatial-reuse of the channel.

We have analysed the performance of Slotted ALOHA with Multiple Directional Antennas (SA/MDA) and found that the throughput and the expected progress of SA/MDA are always higher than those using one omnidirectional transmitting antenna. When the transmission range increases, the gain could be as much as m, the number of directional antennas used. The optimal transmission with SA/MDA for $m=4$ is attained by $N=13$ and $p=0.22$ which gives $S=0.084$ and $Z\sqrt{\lambda}=0.13$.

Besides SA/MDA, we have proposed a new protocol suitable for the multihop PRNs termed as Multi-Tone multiple access with Collision Detection using Multiple Directional Antennas (MTCD/MDA). We have verified the correctness of the protocol and discussed the boundary problem and its solution. An acknowledging scheme using Extended Busy tone (EB/ACK) suitable for the MTCD/MDA protocol has also been introduced.

We have analysed the slotted non-persistent version of MTCD/MDA for randomly distributed stations and deterministic lattice networks. For randomly distributed stations, the maximum values of throughput and expected progress are attained at p=m/N. When the packet length is doubled, the maximum value increases by 30 percent. When compared to SA/MDA, the optimal throughput and expected progress of MTCD/MDA are about three times higher. We have found that for m=1, the maximum value of Z is obtained when N=7. If m=4, the optimal expected progress is attained at N=13, which is the same as that of SA/MDA.

It is suggested that more detailed design should be involved to optimize the performance of MTCD/MDA. Besides the transmission radius R, the number of directional antennas used m and the transmission probability p, the optimization problem could include the following parameters:

(1) The broadcasting angle of the directional antenna θ — it is clear that θ should be around 360/m degree. If a greater angle is used, the transmission interference would be larger. This reduces the spatial-reuse effect and leads to a lower throughput. However, if a smaller angle is adopted, staiions located near the boundary of broadcasting regions would have a greater probability of not receiving packets destined to them.

(2) The number of different busy-tones b — in the present MTCD/MDA protocol presented, we have set b to be equal to m. Actually, we can modify the protocol to reduce the

number of busy-tones used. If fewer busy-tones are used, more bandwidth of the channel can be allocated for data packet transmission. But the modified protocol might prohibit some potentially successful transmissions. Efforts are needed to investigate the overall effect on the performance.

A more detailed analysis, which may involve the Markovian model, is needed to evaluate the long-time overall mean of the throughput and the expected progress. The difficulty in analysis is mainly due to the dependencies between the activity of different stations. Moreover, it is suggested that the analysis should be extended to include the capture effect and the variable packet length case. The packet delay in the network need also be evaluated.

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APPENDICES

APPENDIX 1 : DERIVATION OF THE OPTIMAL PROBABILITY p* IN FORMULA (2.4).

From (2.3), we have

$$S(p,N,m) = p(1-p)(1-e^{-N})e^{-pN/m} \quad .$$

Differentiate both sides with respect to p, we get

$$\frac{d}{dp}S(p,N,m) = (1-e^{-N})e^{-pN/m}[(1-2p)+(p-p^2)(-N/m)] \quad .$$

For maximum S(p,N,m), we put $\frac{d}{dp}S(p,N,m) = 0$ and solve for p, then

$$p = \frac{(N+2m) \pm \sqrt{N^2+4m^2}}{2N} \quad .$$

Since 0 <= p <= 1, we choose

$$p = p^* \triangleq \frac{(N+2m) - \sqrt{N^2+4m^2}}{2N}$$

$$= \frac{2m}{(N+2m) + \sqrt{N^{2+}4m^2}} \quad ,$$

which is formula (2.4).

APPENDIX 2 : DERIVATION OF P_{NAQ}, THE PROBABILITY THAT A STATION IS NOT ACTIVELY TRANSMITTING TOWARDS A CERTAIN DIRECTION.

Let p_a be the probability that a station is active during a slot, and station J be a neighbour of Q. Then

Prob[J is not actively transmitting towards Q's direction |J has h neighbours in Q's quadrant and J has totally k neighbours]

$$= (1 - \frac{h}{k} p_a) \quad .$$

Let Prob[h|k] be the probability that J has h neighbours in Q's quadrant given that J has totally k neighbours. Then

$$\text{Prob}[h|k] = \binom{k}{h} (1/m)^h (1-1/m)^{k-h}$$

and

$$P_{NAQ} = \sum_{k=0}^{\infty} \left\{ \sum_{h=0}^{k} (1- \frac{h}{k} p_a) \text{ Prob}[h|k] \right\} \text{Prob}[A_k]$$

$$= \sum_{k=0}^{\infty} \left\{ \sum_{h=0}^{k} (1- \frac{h}{k} p_a) \binom{k}{h} (1/m)^h (1-1/m)^{k-h} \right\} [\frac{N^k}{k!} e^{-N}]$$

$$= \sum_{k=0}^{\infty} (1-p_a/m) \frac{N^k}{k!} e^{-N}$$

$$= (1 - p_a/m) \quad .$$

In SA/MDA, $p_a = p$, therefore

$$P_{NAQ} = 1 - p/m$$

for SA/MDA.