IEEE 802.11

Wireless Access Method and Physical Layer Specifications

TITLE: TRADEOFF BETWEEN MODULATION BANDWIDTH EFFICIENCY AND MEDIUM REUSE EFFICIENCY

DATE: 5 March, 1991

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1 INTRODUCTION

To a certain extend the development of a MAC protocol and the design of a PHY layer can be carried out independently. However some dependencies exists. This contribution shows the impact of the SNR, which is required for reliable communication, on radio medium reuse. The required SNR is directly related to the modulation bandwidth efficiency and the complexity of the detector, which both are important issues in the PHY layer.

If one defines a PHY layer, without taking into account the architectural wish of medium reuse, one would try to optimize the modulation bandwidth efficiency, and therefore the raw bitrate, by making the SNR per bit as high as possible. This in turn can be accomplished by using a transmit power as high as allowed or economically feasible.
However, there is only one radio frequency spectrum, therefore this medium has to be used efficiently. The attenuation of radio signals makes separation by distance possible. So frequencies can and should be reused over distances as closely as possible. One way to achieve this goal is to develop a cellular system.

Basically the average bitrate per squared or cubic meter, denoted by Z, should be maximized. Z can be expressed as follows:

$$Z = R * \eta / A \qquad [1]$$

with

R	bitrate
η	medium reuse efficiency
A	cell size

The medium reuse efficiency η is defined as the percentage of cells, in which reliable transmissions can take place simultaneously.
The subject of this contribution is the maximization of Z, under the constraints of a fixed bandwidth W, and a fixed cell size A. Theoretically Z can be made arbitrarily large, by making A arbitrarily small. The cell size is easily controlled by the transmit power. In practice A can not be made arbitrarily small. One cell or BSA should cover a certain minimum area, such that for example a typical office floor can be serviced by one cell. Such a zero infrastructure capability is important for a high volume of the potential market. Of course, this does not exclude the possibility to set up a signal distribution infrastructure with decreased cell sizes to obtain higher performances.

For the bitrate R holds:

$$R = \mu * W \qquad [2]$$

with

W	bandwidth
μ	modulation bandwidth efficiency

Considering [1] and [2], the maximization of Z under the constraints of fixed bandwidth W and fixed cell size A, simplifies to the maximization of $\eta * \mu$. This modulation bandwidth efficiency, medium reuse efficiency product, further on denoted by σ, has some interesting properties, which will be shown in the next paragraphs.

Some assumptions are made in the derivation of the optimum σ. These assumptions make the optimization tractable, but may not be appropriate for indoor environments. This analysis gives therefore an insight in the mechanism and a direction for further research rather than absolute quantative results.

2 MEDIUM REUSE EFFICIENCY η.

In this analysis an isotropic signal decrease is assumed. A certain space (2-D or 3-D) now is covered by equal sized cells or BSA's. The actual shape of a BSA is of no importance in this analysis. Boundary effects are not taken into account, so it is assumed that the space under investigation contains many BSA's.
With R the distance from an access point to its farthest serviced terminal (defines the size of the coverage area of a BSA) and D the distance between access points at which reliable communication within both BSA's is possible, for the number of channels C necessary to cover the whole 2-D area holds:

$$C_2 \propto [D/R]^2 \quad \text{with } \propto \text{ the 'proportional to' sign} \qquad [3a]$$

For the 3-D case holds:

$$C_3 \propto [D/R]^3 \qquad [3b]$$

The above relationships can be found in for example Jakes, chapter 7 [Jakes].

It seems reasonable to define the medium reuse efficiency η as the inverse of the number of channels C necessary to cover the whole area. This number defines the percentage of BSA's that can be active simultaneously.

$$\eta_2 \propto [R/D]^2 \tag{4a}$$

$$\eta_3 \propto [R/D]^3 \tag{4b}$$

3 MEDIUM REUSE EFFICIENCY η AS A FUNCTION OF SIGNAL-TO-INTERFERENCE RATIO (SIR)

A fixed transmit power is assumed for all stations, so no power control mechanism is supposed. For the averaged received signal power P now holds:

$$P \propto d^{-n}$$

with d the distance between transmitter and receiver and n the attenuation exponent.

Given the center-to-center distance D of BSA's, at which reliable communication is possible (BER < 10^{-X}) and the radius R of a BSA, the worst case SIR occurs in a situation as sketched in figure 1.

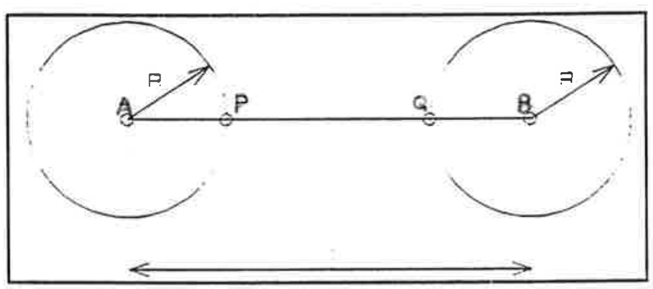


Figure 1

In this worst case situation station Q has to receive access point B, while station P transmits to access point A. For the SIR holds:

$$SIR \propto R^{-n} / (D-2R)^{-n} \tag{5}$$

By combining [4] and [5] the medium reuse can be expressed as a function of the required SIR:

$$\eta_2 \propto [2+SIR^{1/n}]^{-2} \tag{6a}$$

$$\eta_3 \propto [2+SIR^{1/n}]^{-3} \tag{6b}$$

The expressions [6a] and [6b] are plotted in figures 2 and 3 respectively.

4 UPPERBOUND TO MEDIUM REUSE EFFICIENCY, MODULATION BANDWIDTH EFFICIENCY PRODUCT σ.

As can be seen from figures 2 and 3, the medium reuse efficiency η increases with decreasing SIR, required for reliable communication.
However, there is another side of the coin. With decreasing SIR the modulation bandwidth efficiency μ, defined as the ratio between bitrate and bandwidth required, will decrease too. So a tradeoff exists between modulation bandwidth efficiency and medium reuse efficiency. This tradeoff can be shown more explicitly if it is assumed that : 1) the system is supposed to be interference limited and 2) the interference can be treated as Gaussian noise.

For additive white Gaussian noise channels the modulation bandwidth efficiency μ, is upperbounded by the well known Shannon capacity formula :

$$\mu = \log_2(1+SNR) \qquad [7]$$

Combining [7] and [6], together with the assumptions made above, results in a medium reuse efficiency, modulation bandwidth efficiency product σ as a function of SNR and attenuation exponent n.

$$\sigma_2 \propto [\log_2(1+SNR)]*[2+SNR^{1/n}]^{-2} \qquad [8a]$$

$$\sigma_3 \propto [\log_2(1+SNR)]*[2+SNR^{1/n}]^{-3} \qquad [8b]$$

Plots of σ_2 and σ_3 are given for 3 values of n as a function of the SNR in figures 4 and 5 respectively.

5 M-PSK EXAMPLE

Expression [8] gives an upperbound on σ. Without running ahead of the choice for an appropriate modulation scheme, the same calculations may be carried out for M-PSK.
A SNR of 10 dB yields for 4-PSK a BER of approximately 10^{-3}. Increasing the modulation bandwidth efficiency by 1 bit/sec*Hz requires about 6 dB. For the modulation bandwidth efficiency μ in case of M-PSK modulation holds:

$$\mu = \log_2(M) \qquad [9]$$

The 6 dB and 10 dB figures mentioned above, together with [9], are used to obtain expression [10], in which the relation between modulation bandwidth efficiency μ and required SNR for M-PSK is given.

$$\mu = [2 + 10*\log_{10}(SNR)] / 6 \qquad [10]$$

Combining the expressions [4],[9] and [10], together with the already discussed assumptions about noise-like interference and interference limited systems, σ can be calculated. σ_2 and σ_3 are sketched in figure 6 and 7 respectively, for n=2,3 and 4 as a function of the number M. Optimization of the number of levels M, in order to maximize σ_2, leads to a choice of M=4 in case n≤3, as can be seen from figure 6. A similar result is found by D. Cox [Cox].

6 DISCUSSION AND CONCLUSIONS.

Under the assumptions of a fixed bandwidth W, a fixed cell size A and an isotropic signal decrease, in interference limited systems, the average bitrate per squared or cubic meter reaches a maximum, for a specific SNR. This maximum as well as the SNR value depend upon the attenuation exponent n.

In general the maximization of the medium reuse efficiency, modulation bandwidth efficiency product $\eta * \mu$ leads to relatively small values for the modulation bandwidth efficiency μ. This result may also influence the answer to the question of how much bandwidth is needed in a special dedicated frequency band for radio data communication.

Dividing up a fixed bandwidth into N channels does not affect the average bitrate per squared meter. The bitrate R will decrease with a factor N, while the medium reuse efficiency η will increase by a factor N. From a performance point of view it seems not wise to choose for frequency division multiplexing. A flexible time division multiplexing scheme, controlled by the MAC protocol, will under low load conditions lead to a higher performance.

It is important to notice that the assumptions made in this contribution, which are used to derive the above results, do not hold in practical situations, i.e. in indoor radio environments. Figure 8[1] shows a floorplan of an office, in which one transmitter is located. Further it shows equal signal strengths contours. These contours are far from circular shaped. A cellular approach with reasonable sized cells, based upon a statistical description of the radio propagation effects, will probably not work in such an environment.

In my opinion the "capacity of buildings" can not be estimated based upon a cellular approach, due to the highly anisotropic signal attenuation characteristics as well as boundary effects. Further research has to be carried out to obtain information about the relationships between capacity and for example the number of access points and the placing of access points.

7 LITERATURE

[Cox] Universal Digital Portable Radio Communications - Donald C. Cox
Proceedings of the IEEE, Vol. 75, No. 4, April 1987

[Jakes] Microwave Mobile Communications - Edited by W.C. Jakes
John Wiley and Sons, 1974

[1] This figure is extracted from a paper by S.Y. Seidel and T.S. Rappaport titled "900 MHz path loss measurements and prediction techniques for in-building communication system design".

Medium reuse efficiency in case of 2-D space

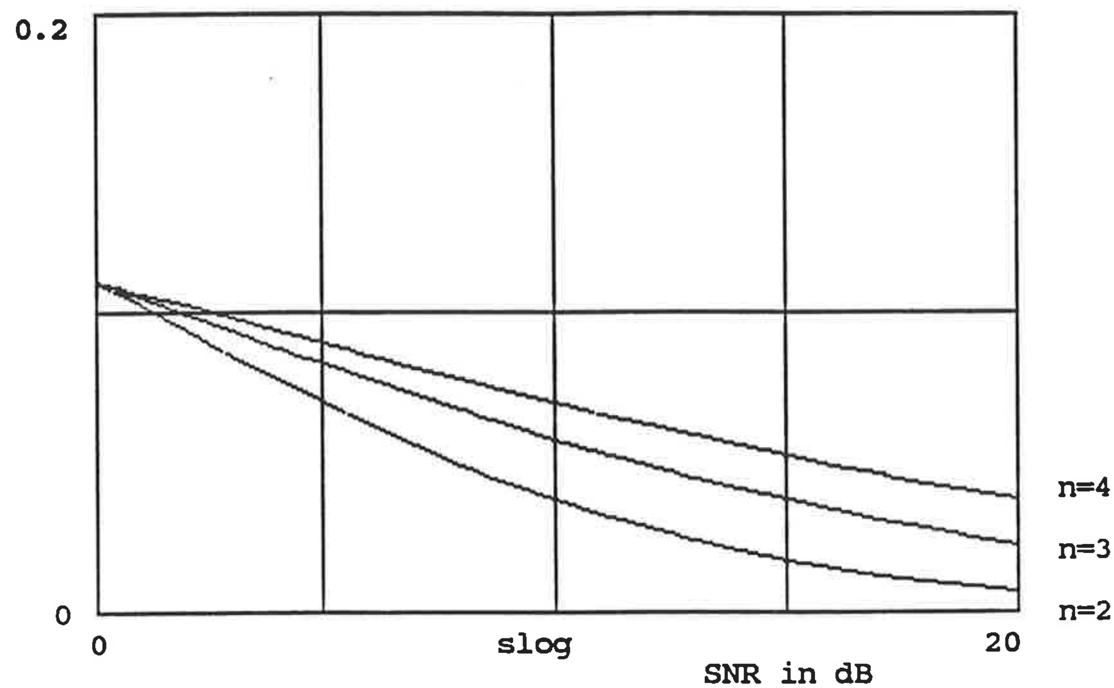


FIGURE 2

Medium reuse efficiency in case of 3-D space

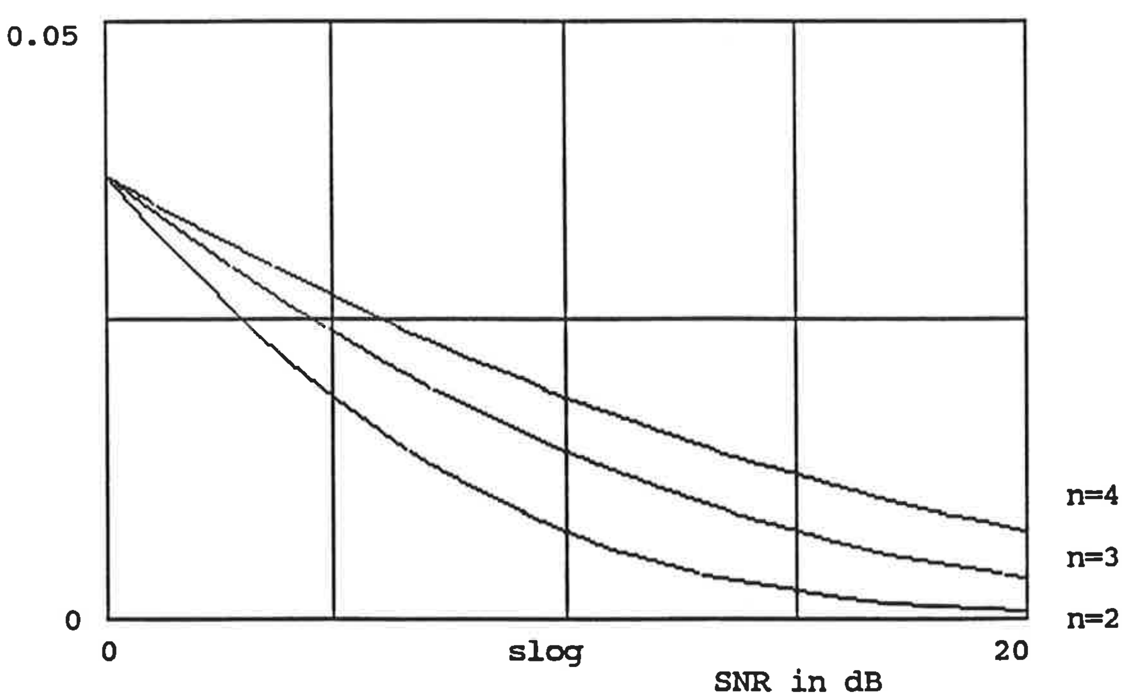


FIGURE 3

Medium reuse efficiency, bandwidth efficiency
product in case of 2-D space

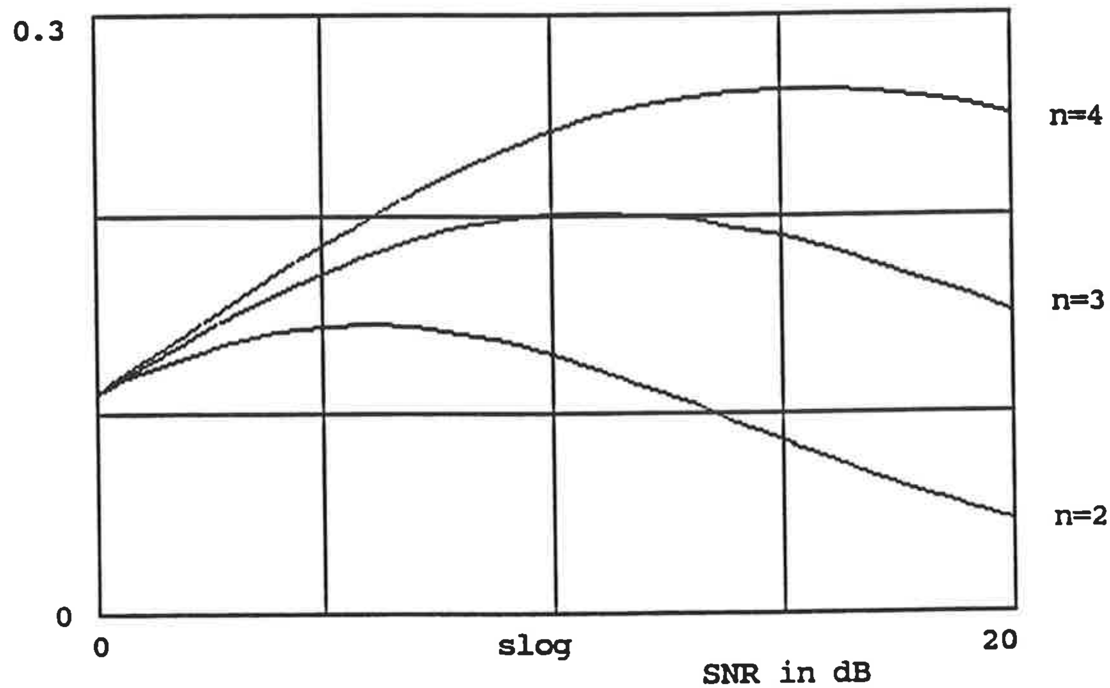


FIGURE 4

Medium reuse efficiency, bandwidth efficiency
product in case of 3-D space

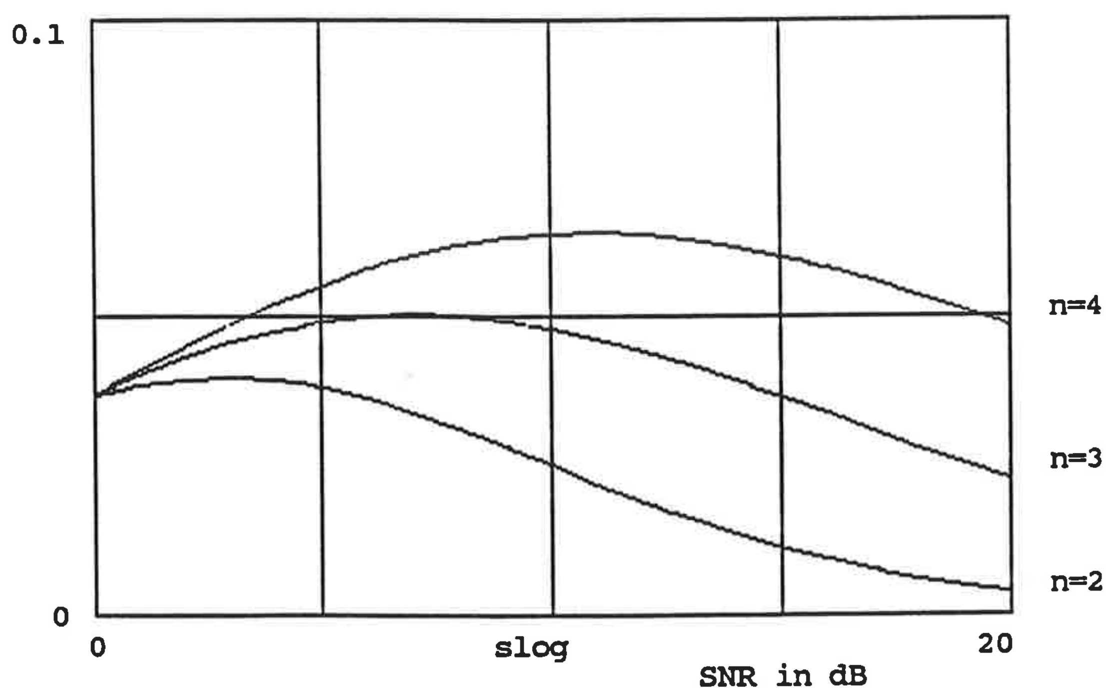


FIGURE 5

Medium reuse, bandwidth efficiency
product in case of 2-D space for M-ary PSK

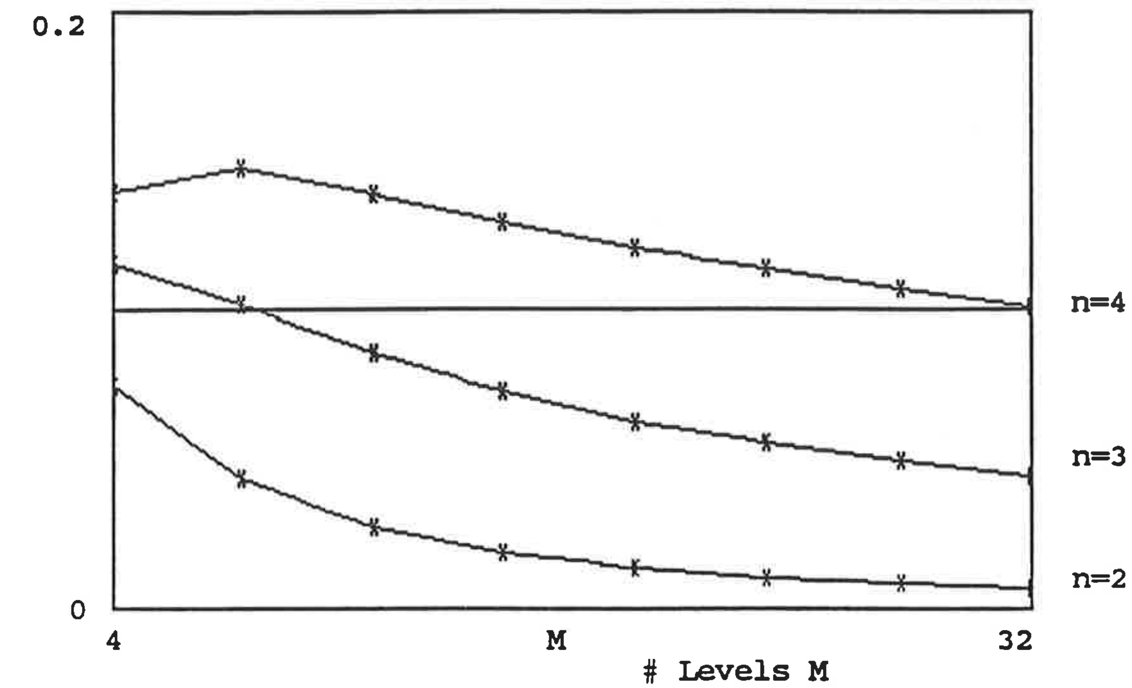


FIGURE 6

Medium reuse, bandwidth efficiency
product in case of 3-D space for M-ary PSK

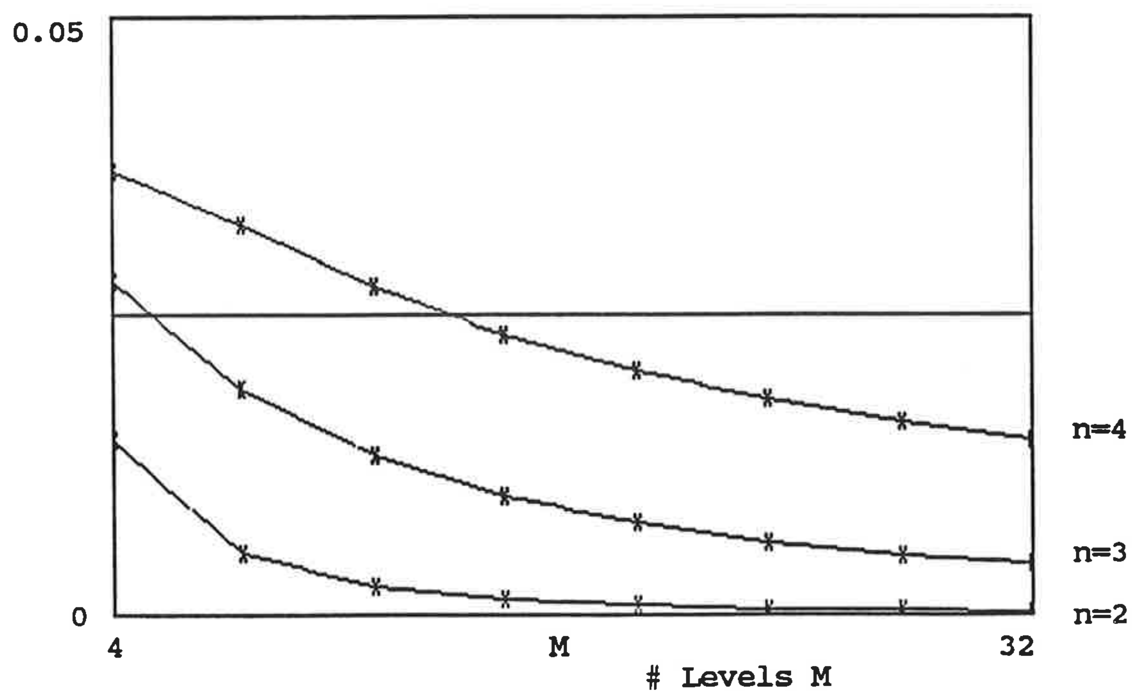
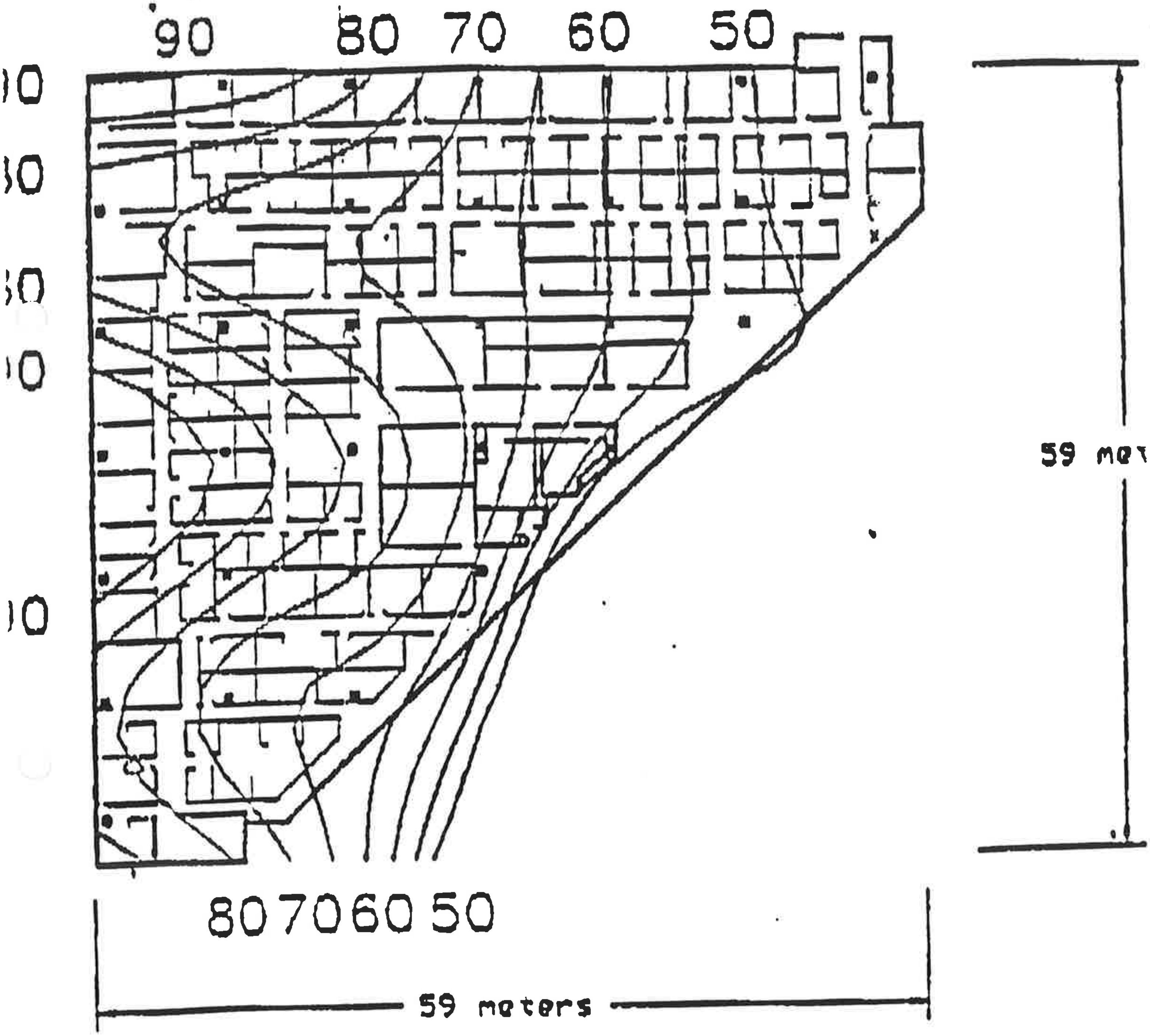


FIGURE 7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