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802 LAN Access Method for Wireless Physical Medium

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TITLE: **DATA CAPACITY OF RADIO SPECTRUM**

SUMMARY

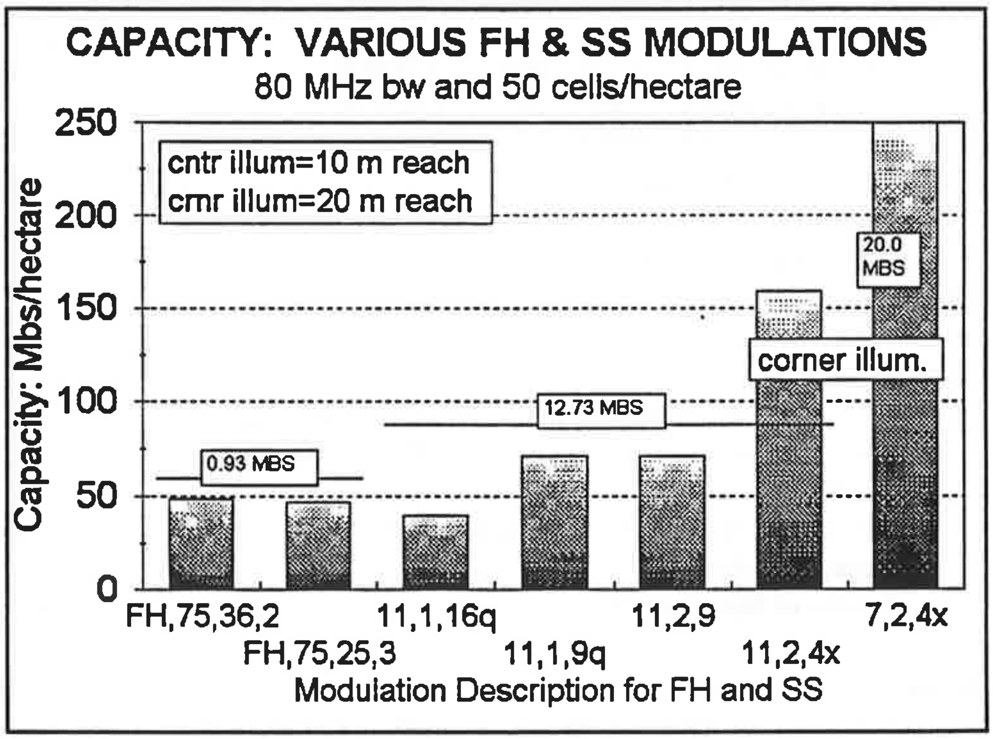

Figure 4 Capacity in Mbps/hectare for Various Frequency Hopping and Spread Spectrum Modulations for a Given Allocated Bandwidth and Cell Size

To compare short reach radio modulations and system plans, it is necessary to estimate the capacity of radio spectrum with methodology that will accommodate widely different transmission technologies.

The problem is separated into two parts:

Spectrum capacity and Capacity utilization.

The first category, is the subject of this paper; and it produces a *result which is independent of the access method* employed and of the use of the capacity provided.

DATA CAPACITY OF RADIO SPECTRUM

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Note:
A revision is expected at a future date.--CAR 9JUL93 Print: July 11, 1993

DATA CAPACITY OF RADIO SPECTRUM

SUMMARY

To compare short reach radio modulations and system plans, it is necessary to estimate the capacity of radio spectrum with methodology that will accommodate widely different technologies.

Separation of Capacity and Utilization

The problem is separated into two parts:

Spectrum capacity

Capacity utilization

The first category, is the subject of this paper; and it produces a *result which is independent of the access method* employed and of the use of the capacity provided. Techniques for utilizing this capacity are in the second category which will be addressed in a separate paper.

An example application of this approach uses radio methods presented to the IEEE 802.11 standards Committee. The results are normalized to unit area served, a point absent from current proposals.

Fading and Error Rate Floor

There is a floor on bit-error-rate which cannot be corrected by workable increases in signal level in the presence of fading. The techniques which mitigate this problem are also those that minimize "capture ratio" (the necessary signal-to-interference ratio for low error rate).

It is a necessary condition that signal level be above some threshhold at the receiver, but it is not a sufficient condition for accurate data transfer. Many proposals overlook this critical point.

Since many of the measures necessary to overcome this problem result in lower yield from spectrum, it is necessary to qualify evaluation candidates in this regard.

Frequency Reuse Plan

A difficulty with many other evaluations is absence of a defined method of frequency reuse. Simulation has been used as a tool to show function where there is no plan. Much of the detail of these simulations involves randomizing detail location of stations which has little effect on the interference background. Also, the results presented are for a particular access method.

Frequency reuse must be taken into account from the beginning of system design. The system cannot be designed for high capacity by starting with a single channel and assuming that overlapping coverage can be later resolved with additional parallel channels.

Inputs and Outputs

The *inputs* to the estimation process are:

a) allocated spectrum bandwidth,
b) maximum reach or cells/hectare
c) reuse factor dependent on coverage reliability, protection ratio, system configuration and signaling accuracy;
d) bits/Hz for the modulation employed
e) modulation specific parameters
   e.g. symbol description for ss

The *outputs* are:

f) Mbps/hectare,
g) Mbps/hectare/MHz of spectrum

Calculation Formula

capacity/hectare =
(capacity/cell) x cells/hectare

capacity/cell =
transfer rate in Mbps /reuse factor

transfer rate =
bits/Hz x total allocated bandwidth x F(m)

Fss = bits per symbol /chips per symbol

Ffh =(no. hopping chnls)/min channel sep'n

Ftdm = Fam = Ffm = 1

<u>Outputs</u>

capacity/hectare =
(cells/hectare) x transfer rate/reuse factor

capacity/hectare/Mhz bandwidth =
(capacity/hectare)/(total allocated bw)

BIT-ERROR-RATE IN FADING

Fading of the desired signal is commonly described by the following probability distributions:

Rician: for short optical paths
Rayleigh: for cluttered semi-optical paths
log-normal: for large obstacle shadowing

Of these, Rician is less severe, Rayleigh is the most common, and log-normal is used only for area coverage probability.

The magnitude (standard deviation) of Rician and Rayleigh probabilities is lower for wider bandwidth signals, because the fades are then frequency selective degrading only a fraction of the channel width. The advantage of direct sequence spread-spectrum signal bandwidths of 40 MHz or more shows up as reduced fade margin relative to slow symbol rate narrowband modulations.

Table I shows fading channel bit-error-rates.

TABLE I. BIT ERROR PROBABILITIES FOR BINARY ORTHOGONAL SIGNALING, SLOW NONSELECTIVE FADING, AND NONCOHERENT DEMODULATION

	Bit Error Probability		
$(E_b / N_0)_{dB}$	Rayleigh	Rician $g^2 = 0.1$	No Fading
4.0	2.22×10^{-1}	1.61×10^{-1}	1.42×10^{-1}
6.0	1.67×10^{-1}	9.15×10^{-2}	6.83×10^{-2}
8.0	1.20×10^{-1}	4.18×10^{-2}	2.13×10^{-2}
10.0	8.33×10^{-2}	1.51×10^{-2}	3.37×10^{-3}
12.0	5.60×10^{-2}	4.41×10^{-3}	1.81×10^{-4}
14.0	3.69×10^{-2}	1.13×10^{-3}	1.76×10^{-6}
20.0	9.80×10^{-3}	2.48×10^{-3}	9.64×10^{-23}

From: "Reference Data for Engineers: Radio, Electronics, Computer, and Communications--Seventh Edition;" Page 24-23, H. W. SAMS and Co., 1986; ISBN: 0-672-21563-2

While the above data (Table I) was derived for signal-to-noise rather than signal-to-interference ratio, a conglomerate of like-type signals will resemble noise for this purpose. Notice should be taken of the "nonselective fading" assumption which applies to narrowband systems. Selective fading occurs only in a wide bandwidth, and may have a much smaller effect on the total received signal during a fade.

The main conclusions drawn are:

a) Fading is a primary consideration, and a motivation for any means of mitigation.
b) Simple increase of signal-to-noise ratio is an ineffective remedy for fading.
c) *For simple systems, there is a floor on bit error rate from which no further improvement is possible*, and that *floor is near 1×10^{-2} for non-optical paths and only four times better for optical paths.*

The noncoherent demodulation assumed in this table is the better assumption in a multipath medium where rf phase information can be lost.

To penetrate this error rate floor, the following are possible methods:

i) polarization, direction or space diversity with two or more receiver ports.
j) coverage diversity with overlapping coverage from two or more access-points.
k) space diversity through resolution and separate evaluation of time delayed propagation paths.
l) selection of cell size so that coverage area is largely optical paths (Rician fading) and interference is cluttered path (Rayleigh fading).
m) narrow beam directional antennas on at least one end of the path.
n) forward error correcting channel codes
o) automatic retransmission of faulty messages

Using simulation analysis, K-C. Chen et al in 802.11-92/130 shows the same error rate floor and the value of diversity and FEC in Figures 7 to 18. The work in this analysis is important in arriving at a satisfactory system.

To be qualified, proposed PHY layers must address the fading problem.

THE REUSE FACTOR

The reuse number is the number of non-interfering separate coverage areas necessary to obtain near 100% area coverage. With wide deviation FM radios capturing at 6 dB above interference, and with a not too stringent requirement for absence of noise bursts, values no lower than 7 were used in early design of cellular telephone systems (now, new stations are put where the need exists regardless of geometric generalities). Sample calculations seem to require a reuse factor of 21 for an attenuation/distance slope of 38 dB/decade for a reliable separation. A reuse factor of 7 was originally associated with 120° sectoral coverage base stations. Actual observed performance with small reuse numbers is adequate except with traffic saturation and near 100% duty cycle.

In LAN, artful radio design in which walls are used rather than ignored, will enable lower reuse factors.

For square cells (a convenient and sufficiently accurate assumption for evaluation), the potential reuse factors are 4, 9, 16 and 25. Their ranking and likely use may be as follows:

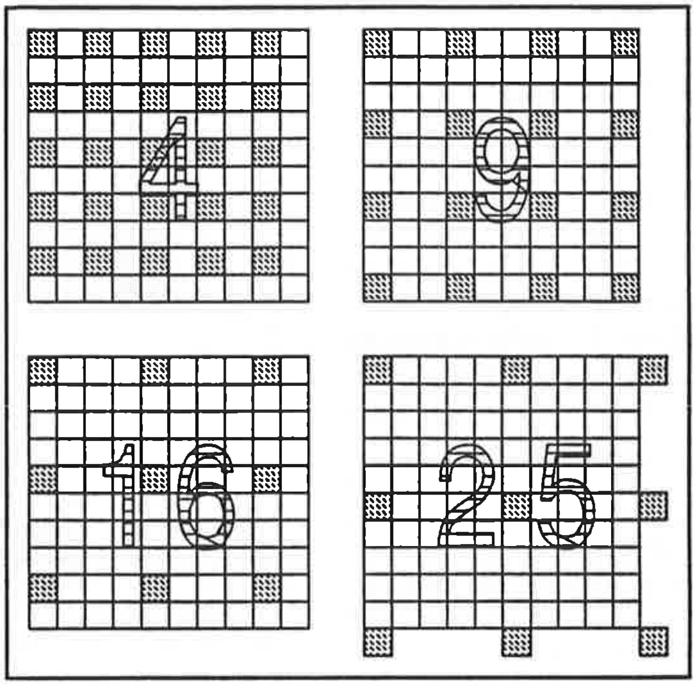

Figure 1 Geometry of Frequency Reuse in a Pattern of 100 Cells for Values: 4, 9, 16, 25

Table II – Reuse Factors

25 *normal peer-to-peer*, all omni antennas, no power control, carrier sensing access
16 *improved peer-to-peer* with minimum S/I modulation, protocol access, diversity, and optimized reach
9 *omni-access-point based* systems with protocol access, optimized reach
4 *capacity maximized systems* requiring also minimum S/I modulation, sectorized access-point antennas and diversity

Evaluation of Reuse Factor

The reuse factor is evaluated considering:

1) the required S/I for satisfactory operation.
2) the degree of Rician or Rayleigh fading and its statistics after mitigation by wide-banding, diversity and directional antennas
3) the statistical probability of interference conditions with representative activity

The reuse factor is widely used in the context of interference between base stations (access-points) at a station receiver. Since station-to-station path attenuation is much higher, the interference between stations is rarely considered.

The assumed distance ratios for reuse factors 2 to 5 are shown in Figure 2 on the following page. If all nearby cochannel base stations are simultaneously in use, the actual interference level is at least four times greater (power sum) considering the first ring, and then further increased by the second ring of four at 1.4 times the distance of the inner ring.

Location Probability of Excess Interference

There is another way to present the effect of varying reuse distance shown on Figure 2. The effect of decreasing the reuse number is not abrupt, but rather a continuous increase in the location probability of insufficient margin between desired and interfering signals. For the various reuse factors shown--12, 21 and 33--shown, certain distance ratios are associated corresponding to regular hexagonal cell patterns.

Also two different path attenuation factors are shown. The faster the attenuation the better the isolation for any given reuse factor.

This figure is transcribed from a 1982 presentation on cellular system design. The distance attenuation factors were those used by Bell Laboratories in the cellular telephone development in the '70s. The assumptions go with outdoor propagation and FM radio with modulation index of 2, somewhat higher than would be used for data.

This figure shows the relationship between the factors rather than usable absolute values which are particular to the assumed system plan.

There is no brick wall phenomenon when the plan uses too small a reuse number. Instead the service range shrinks and there are more and more places and times when the transfers fail.

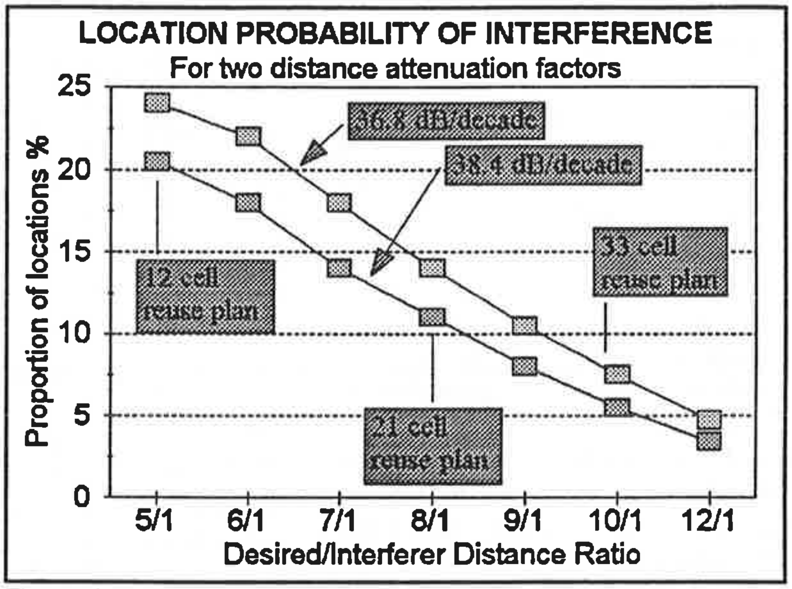

Figure 2 Data from "Cell Site and Frequency Deployment Recommendations," Figure 1.4-1 (pg 20), C. A. Rypinski, Anaconda-Ericsson Communications Division, May '82

Calculation of Observed and Necessary S/I

The following factors contribute to the *observed signal-to-interference ratio* at a point within the coverage area of a single cell:

1) relative path loss for the desired and each interfering signal, and
2) the power summing of the combined effects of all interferers within a few cell radii, and
3) the probability distribution of the level of the desired signal relative to the rms interference level.

The *necessary signal-to-interference ratio* at a receiver includes the following factors:

4) the required S/I under laboratory conditions with like spectrum interferers at desired signal threshhold levels (function of modulation type), and
5) the margin necessary to increase BER to the desired level from that of the S/I test, and
6) the added margin necessary to maintain the signal level above threshhold at least 1% of the time considering Rayleigh or Rician fast fading, and
7) the added margin necessary to provide the coverage in 90-99% of the defined service area.

In addition, the number and distance of interfering stations may be improved by antenna directivity used at the access-points. The analysis is shown for center illuminated cells. Adjustments are added for corner illumination.

These factors are where the relative performance of different modulations and system topologies makes a big difference.

Relative Path Loss for Desired and Interferer Signals

The maximum reach chosen is multiplied by the factor shown in Figure 3 to obtain the distance traversed by the interfering signal at the worst case location considering the power sum of all interfering signals at the nearest and next nearest ring of interferers. It is important that the path attenuation for interfering signals be as high as possible. This occurs naturally as the number of walls and other obstacles increases with distance.

The value of the assumed interference may be reduced by duty cycle assumptions which reduce the average but not the peak value. A duty cycle of 50% for each interferer halves the average interference power.

This method calculates interference effects between access-points. Stations interfering with each other may be neglected because they have a shorter range and a much lower transmitter duty cycle.

For interference considerations in a pure peer-to-peer network, all stations within one cluster may be considered to be concentrated at a point in the aggregate having a high duty cycle. The desired path is the same for either.

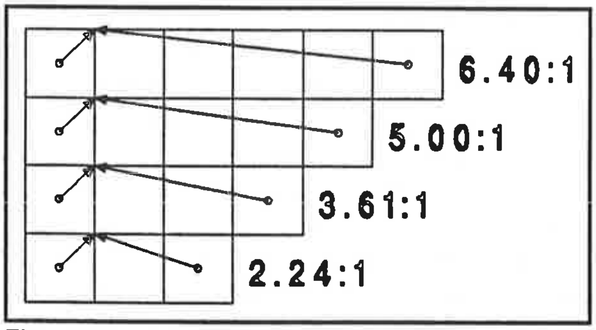

Figure 3 Shows Ratio of Path Length for Desired and One Interfering Signal for Reuse Factors: 25, 16, 9 and 4

Fading and Fade Margin

Overcoming the degradation from multipath caused fast fading is the most important and difficult design problem for high rate data transmission. It cannot be solved either by increased power or by slowing the symbol rate to a fraction of the medium capability.

In narrowband systems, there is inevitable fading for both desired and interfering signals.

As an approximation, it is known that the background level composed of the sum of a number of interferers tends to have much less variability than each of its components. It is therefore *sufficient to use the rms, mean or average values for the interferers to give a constant background. For the desired signal, it is necessary to assume the appropriate fading distribution.*

Propagation and Path Loss Calculation

Traditional calculations for outdoor environments use a nominal average with a largely empirical basis to which adjustments are added for antenna height, radio properties and terrain characteristics. Each adverse environmental factor increases the required transmitter power. No penalty is assumed for to much signal level. The process is different in an interference limited system plan. Also, the possibility of dependence on optical paths in a premises environment requires different emphasis.

The Ericsson-Åkerberg Model

A well-founded loss formula for in-building propagation was given and used in simulations presented by Dag Åkerberg to WINTech in a series of contributions in spring '93 is shown following.

"Path Loss as a function of distance

1) $Loss(d) = L_0 + 10\,n\,\log(d) + k\,Loss_{floor}$

0m < d < 20 m $n=3.0$ L_0 = *loss at 1m = 38 dB*

20m < d < 40 m $n=6.0$ L_0 = *loss at 20m*

40m < d $n=12.0$ L_0 = *loss at 40m*

where d = distance from transmitter to receiver

L_0 = *Unit loss*

n = *power decay index*

$Loss_{floor}$ = *loss per floor separation = 15 dB*

k = *number of floors*

2) Shadow Fading

A log-normal distribution with a mean of 0 and a standard deviation of 8 dB is assumed, and added to path loss.

3) Fast Fading

The fast fading is assumed to be Rayleigh distributed, and that antenna diversity at the base station only is used. This value is subtracted from the shadow faded power. For 1% outage the fade margin is 10 dB."

This is the necessary form for model calculations, however the values of the exponents for the distances above 20 m are in excess of the Author's experience. These exponents are probably accurate averages for paths traversing highly insulated building walls in certain building shapes used by Ericsson Radio in Kista. Substituting 3.8 for 6.0 and 5.0 for 12.0 would be more acceptable for paths entirely within a building.

The high exponent minimizes the interference from separate but nearby user clusters. 12.0 is a numerical approximation of a 40 dB attenuating shield with an inner radius of 40 meters and 20 meters thick.

The positioning of the breakpoints at 20 and 40 meters is reasonable.

The shadow and Rayleigh fading statements are certainly correct for interferers. An 18 dB fade margin on the coverage path within 20 meters is arguable, and will lead to a larger than necessary reuse factor.

1% outage on a voice channel is not bad. A narrowband digital data channel would not produce usable results in the same context.

The NCR-Diepstraten Model

The NCR simulation model results presented in IEEE 802.11-92/51 showed that two clusters of users had to be spaced 10 cluster radii to provide 90% of the total capacity of two clusters. This indicates that a reuse factor of at least 25 would be required for the conditions assumed.

This model assumed that sufficient signal-strength was a measure of low error rate. If this is true, it would be because of skill in implementing the spread spectrum modulation and demodulation; and the conclusion could not be validly extrapolated to slow frequency hopping.

CAPACITY ESTIMATION

The necessary inputs ("givens") are:

1. Allocated system spectrum bandwidth (MHz)
2. Maximum reach (from illumination point to diagonal corner of square cell)
3. Reuse factor – number of non-interfering independent coverage areas (often separate channels) necessary for continuous area coverage
4. Modulation factor in bits/Hz of:
   a. frequency separation between adjacent but independently usable channels, or
   b. bandwidth in which energy radiation in an adjacent channel is just within limits
   including benefit from use of quadrature phase
5. (Spread spectrum) Length of symbol in chips and the number of bits transferred per symbol from which the data throughput rate is derived.
6. (Frequency hopping only) Number of hopping channels and number of available channels derived from minimum separation between independently usable channels by unrelated nearby stations. From these inputs, the maximum number of available channel patterns and the number of patterns per coverage are derived.

From these inputs a number of necessary derived values are found including the area of a discrete coverage (now called "cell"), and the fraction of the available bandwidth capacity which can be assigned to each cell.

Considerations in Selecting Maximum Reach

The shorter the reach, the higher the capacity and the easier the radio function. Cost of infrastructure may increase with larger numbers of access-points per hectare for an infrastructure based system. Since access-points may be more powerful and complex for longer reach and increased multipath, this is not an obvious cost tradeoff.

The first break in the distance vs. attenuation relationship (this is 20 meters in the Åkerberg model presented to WINTech) is a good first choice for reach. At this range, the more distant interfering signals will be attenuated at a higher rate than the desired signal.

Once the maximum reach is selected, the dimensions of the cell are determined. Use of corner illumination of cells is an option doubling the reach required for a given service area. The longer reach is compensated by antenna gain.

Shown following are the relationships between reach and other dependent parameters.

Table III – Reach and Values of Dependent Parameters

Reach--meters Center Illum.	Reach--meters Corner illum.	Cell dimension Side length--m	Cell dimension Area--m²	No. of Cells per hectare
7.07	14.14	10	100	100
10	**20**	**14.4**	**200**	**50**
14.14	28.8	20	400	25
20	40	28.8	800	12.5
28.8	57.6	40	1600	6.25

Note: Boldface values used in example evaluation

Selection of the Modulation Factor

The *bits per Hz* value may be associated with the limiting n db down bandwidth of the out-of-band radiation. In this estimate, a) and b) are not significant. The necessary bandwidth is that where the level of interference created for other users is acceptable considering the spectrum of the transmitting station and the topology in which it is used.

A smaller required margin against like-type signals (capture ratio) is an important property of a desirable modulation. Two-level modulations have overall advantage against multi-level modulations for this reason.

Examples of commonly considered digital modulations are: a) 4CPFSK, b) GMSK, c) OQPSK and 2QAM or BPSK ranging from .7 to 1.8 for this factor. Newer proposals offering improvements in bits/Hz would be in the high end of this range.

EXAMPLE CAPACITY ESTIMATES

Figure 4 above shows the use of the formulas and values described to estimate the capacity of a given amount of spectrum providing coverage for one hectare among several. The complete tabular form of this information is shown in Table IV following.

Channelized Systems

The estimate is blind as to whether capacity is divided into channels by time or frequency division. The answer is the same for 9-one MHz channels as for 1-nine MHz channel. It is also blind to peak transfer rate requirements.

Frequency Hopping Systems

The system chosen is synthetic to illustrate the method, but not far removed from what is actually proposed. With 75 hopping channels, it is assumed that use of every third channel will allow 25 simultaneous communications within a service area comprised of many autonomous clusters that do not interwork.

For the FH75,25,3 example, the reuse factor is 25. The cell is an area within which users of one hopping pattern are clustered and interworking. The reuse factor gives the separation before an interfering or identical hopping pattern can be reused as shown in Figure 3. The intervening cells each must use a different pattern.

Most of these systems intend to have a much larger service range than the 10 meters assumed. One consequence of using a much larger range is that the service area will extend beyond the range where unobstructed propagation can be expected. This, along with the probable use of peer-to-peer mode and high transmitter power, will cause the necessary separation of interfering patterns by greater multiples of the service range.

The factors used are thought to be on the optimistic side for FH considering that the channel is narrow band.

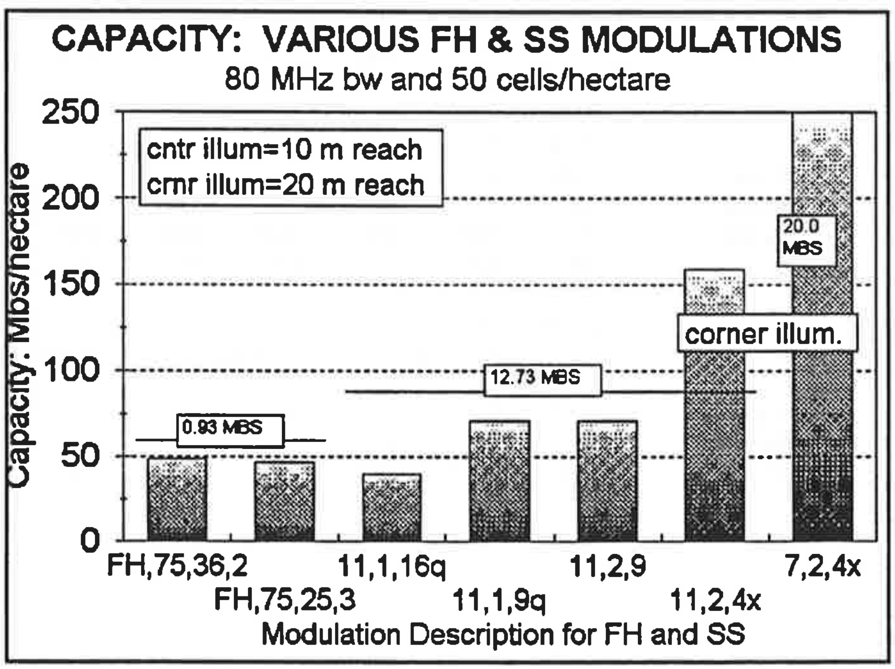

Figure 4 Capacity in Mbps/hectare for Various Frequency Hopping and Spread Spectrum Modulations for a Given Allocated Bandwidth and Cell Size

Spread Spectrum Systems

Two types of 11-bit symbol spread spectrum systems are shown. One obtains a double of data throughput by using a parallel quadrature phase channel (suffix "q"), and the other obtains a double using 2 bits per symbol.

The *quadrature phase* plan is offered for a dominantly peer-to-peer or peer-to-server system plan in which there is no enhanced shared access-point. All equal omni-directional antennas are assumed. The system is shown for reuse factors of 9 and 16. Offered simulation information suggested that a reuse factor of 25 or more would be necessary without introduction of power control. The 11,1,9q plan would require appropriately designed access points rather than a peer-to-peer plan to realize the capacity estimated.

There should be no assumption that a narrow band channel used in frequency hopping, would allow an equally low reuse factor.

For comparison the *11,2,9 plan* does not use quadrature phase and does use 2-bits/symbol. The capacity with reuse factor 9 is identical to that of the q plan.

The corner illuminated plans (suffix "x") provide much more capacity because of the smaller reuse factor. The access-point uses quadrantally directive antennas and other refinements. Improved capture ratio modulation is also desirable for the smaller reuse factor.

The 7,2,4x type has a transfer rate 11/7ths times that of 11,2,4x resulting in greater utilization of the 80 MHz spectrum allocated.

Table IV – CAPACITY CALCULATOR

GIVENS:								
Allocated Frequency Spectrum:	MHz	80	80	80	80	80	80	80
Modulation factor:	bit/Hz	0.875	0.875	1.750	1.750	0.875	0.875	0.875
Maximum reach	meters	10.00	10.00	10.00	10.00	10.00	20.00	20.00
Reuse factor:	n	36	25	16	9	9	4	4
SS--Chips per symbol:	cp/sym			11	11	11	11	7
SS--Bits per symbol:	b/sym			1	1	2	2	2
FH--No. hopping frequencies:	n	75	75					
FH--Min channel separation:	n	2	3	(3 means every third channel is used)				
DERIVED VALUES:								
SS--Chip rate:	Mcps/MHz			140	140	70	70	70
SS--data rate:	Mbps			12.73	12.73	12.73	12.73	20.00
SS--Capacity/cell:	Mbps			0.80	1.41	1.41	3.18	5.00
FH--Max no. chnl patterns:	n	37.5	25					
FH--max avg no. chnls/cell:	n	1.04	1.00					
FH--data rate per pattern (chnl):	Mbps	0.93	0.93					
FH--capacity per cell:	Mbps	0.97	0.93					
Length one side:	meters	14	14	14	14	14	14	14
Area	sqr mtr	200	200	200	200	200	200	200
Cells/hectare:	n	50	50	50	50	50	50	50
MODULATION IDENTIFIER:		FH,75,36,2	FH,75,25,3	11,1,16q	11,1,9q	11,2,9	11,2,4x	7,2,4x
CONCLUSIONS:								
Capacity per cell:	Mbps	0.97	0.93	0.80	1.41	1.41	3.18	5.00
Capacity/hectare:	Mbps/ha	48.6	46.7	39.8	70.7	70.7	159	250
Capacity/hectare/MHz:	Mbps/ha/MHz	0.61	0.58	0.50	0.88	0.88	1.99	3.12

CONCLUSION

Capacity can be estimated for different modulations and systems as demonstrated. The methodology is non-judgmental of fading resistance and access method, however the factors affected are identified.

The Table below gives the Author's opinion on the relative priority of functions in maximizing capacity and the proportion of successful transfers.

TABLE V
PRIORITY OF OPTIMIZATION

1) REUSE FACTOR
2) Setting reach to first break in path loss
3) CAPTURE/ PROTECTION RATIO
4) Maximized channel bandwidth
5) Maximized "eye" opening modulation = two-level
6) Space and Time Diversity
7) PATH REDUNDANCY
8) MODULATION EFFICIENCY (bps/Hz)
9) Proportioning to impulse response

The quantitative importance of the reuse factor 1) has been shown, but the elements that enable a low factor may not be widely understood or in the alternative disregard for the need for a large scale, high capacity system.

A low factor requires selection of a reach where interference is attenuated at a higher rate than the signal within the service range 2).

The capture ratio 3) is the signal-to-interference ratio required under laboratory conditions, and this is one of the elements within protection ratio where margins for fading are included.

Channel bandwidths of 40-140 MHz 4) have the right proportions to cause selective fades to affect only a fraction of the transmission bandwidth. Because of allocation limits and the cost and battery drain of high speed logic it is unlikely that there will be advocacy for excessive bandwidth.

The maximum "eye" opening 5) in amplitude is the peak to peak amplitude of the signal and the maximum width is one bit interval. Almost all modulations that have higher than average spectrum efficiency compromise these proportions principle. Also modulations with intrinsic intersymbol interference will have diminished opening. It is the tolerance in the opening which is used to offset unavoidable noise and interference that also diminish its size.

Space and Time diversity 6) are primarily means of reducing the affect of Rayleigh (fast) fading, and they are implemented at a receiver to increase the success probability of one transmission. This factor is a component of protection ratio which influences the necessary minimum value of the reuse factor.

Path redundancy 7) from duplicate coverage is the primary protection against momentary shadowing, and it works far better than increased fade margin.

A larger bits/Hz factor 8) for the radio modulation is desirable, but not as desirable as minimum capture ratio 6). There are acceptable compromises between these considerations.

The right order of magnitude for a direct sequence spread spectrum symbol is the delay spread of the medium 9). If it is longer, then the time resolution will not maximally offset Rayleigh fading. One of the faults of non-spread modulations is that the multipath shows up as increased fade deviation. A slow transmission rate may mitigate intersymbol interference, but does little for the current symbol.

The selection of these weightings is a direct consequence of quantitative evaluation of capacity. A successful choice of PHY will necessarily quantitatively consider these factors.